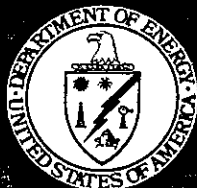


8 179

Nuclear Waste Policy Act
(Section 113)

Consultation Draft



Site Characterization Plan

***Reference Repository Location,
Hanford Site, Washington***

Volume 8

January 1988

U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Washington, DC 20585

PLEASE RETURN TO:
ENVIRONMENTAL DIVISION
RESOURCE CENTER

9 2 1 2 5 5 0 2 2 1

THIS PAGE INTENTIONALLY
LEFT BLANK

SITE CHARACTERIZATION PLAN

Chapter 8 - SITE CHARACTERIZATION PROGRAM

Section 8.3.1.5

Specific Program for Climatic Characterization

~~THIS PAGE INTENTIONALLY
LEFT BLANK~~

TABLE OF CONTENTS

	<u>Page</u>
8.3.1.5 Specific program for climatic characterization	8.3.1.5-1
8.3.1.5.1 Purpose and objectives	8.3.1.5-8
8.3.1.5.2 Rationale	8.3.1.5-9
8.3.1.5.2.1 Regulatory and issues resolution strategy rationale for the program	8.3.1.5-11
8.3.1.5.2.2 Technical rationale for the program	8.3.1.5-20
8.3.1.5.3 Past climatic change investigation	8.3.1.5-24
8.3.1.5.3.1 Purpose and objectives of investigation	8.3.1.5-27
8.3.1.5.3.2 Rationale for investigation	8.3.1.5-28
8.3.1.5.3.3 Description of past climatic change study	8.3.1.5-30
8.3.1.5.3.4 Application of results of investigation	8.3.1.5-47
8.3.1.5.3.5 Schedules and milestones for investigation	8.3.1.5-49
8.3.1.5.4 Future climatic change investigation	8.3.1.5-54
8.3.1.5.4.1 Purpose and objectives	8.3.1.5-55
8.3.1.5.4.2 Rationale for investigation	8.3.1.5-56
8.3.1.5.4.3 Description of future climate change study	8.3.1.5-58
8.3.1.5.4.4 Application of results	8.3.1.5-74
8.3.1.5.4.5 Schedules and milestones for investigation	8.3.1.5-75
8.3.1.5.5 Site meteorology investigation	8.3.1.5-79
8.3.1.5.5.1 Purpose and objectives	8.3.1.5-80
8.3.1.5.5.2 Rationale	8.3.1.5-82
8.3.1.5.5.3 Description of site meteorology study	8.3.1.5-85
8.3.1.5.5.4 Application of results	8.3.1.5-94
8.3.1.5.5.5 Schedules and milestones for investigation	8.3.1.5-94
8.3.1.5.6 References	8.3.1.5-96

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.1.5-1	Hierarchy of climatic characterization program within site characterization	8.3.1.5-6
8.3.1.5-2	Work requirements and analyses included in the characterization of paleoclimates	8.3.1.5-26
8.3.1.5-3	Analyses included in the specific program of investigation of climate change at the Hanford Site	8.3.1.5-31
8.3.1.5-4	Locations of some of the sites in the northwestern United States at which pollen samples have been collected	8.3.1.5-37
8.3.1.5-5	Schedule and selected milestones of the past climatic change investigation	8.3.1.5-50
8.3.1.5-6	Work requirements and analyses included in the forecasts of future climates	8.3.1.5-57
8.3.1.5-7	Schedule and selected milestones of the future climatic change investigation	8.3.1.5-76
8.3.1.5-8	Schedule and selected milestones of the site meteorology investigation	8.3.1.5-95

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.1.5-1	Panel members for site characterization and climate change at the Hanford Site	8.3.1.5-3
8.3.1.5-2	Supporting parameters for performance parameters derived from Issues 1.1, 1.8, and 1.9(b)	8.3.1.5-16
8.3.1.5-3	Data requirements for certain climate-related supporting parameters	8.3.1.5-18
8.3.1.5-4	Studies and study components included in the specific program for investigation of the impact of climatic changes	8.3.1.5-22
8.3.1.5-5	Expertise to be included in the advisory panels for climate change studies	8.3.1.5-23
8.3.1.5-6	Local paleoclimate analyses procedures	8.3.1.5-34
8.3.1.5-7	Glacial geological analyses procedures	8.3.1.5-43
8.3.1.5-8	Paleo-oceanographic analysis procedures	8.3.1.5-46
8.3.1.5-9	Procedures for global climate change local modeling study components	8.3.1.5-67
8.3.1.5-10	Estimated likelihood of success of model components and alternative strategies	8.3.1.5-73
8.3.1.5-11	Supporting parameter table for the meteorologic elements of radiologic safety issues	8.3.1.5-86
8.3.1.5-12	Site meteorology analyses procedures	8.3.1.5-89

9212550225

This page intentionally left blank.

9 2 1 2 5 5 5 0 2 2 2 6

8.3.1.5 Specific program for climatic characterization

Acceptable performance of the proposed Hanford Site geologic repository depends in part upon the prevention of unacceptable levels of radiation exposure to Hanford Site workers and members of the general public. During the period of repository operation, meteorologic conditions can affect the performance and safety of repository activities. In the event there was a significant release of radioactive material to the atmosphere, meteorologic conditions would play an important role in determining the environmental impact of the release. After repository closure, climatic conditions could strongly influence whether the rate of transport of radionuclides released by the waste package system through surrounding saturated rock would be slow enough to meet regulatory requirements for exposure within the accessible environment. This radionuclide transport is directly controlled by geochemical condition and groundwater travel time. In turn, groundwater travel is controlled in part by rate of recharge, which is directly linked to specific climatic parameters. Because of the important role of atmospheric conditions on repository performance, regulatory requirements are directly linked to certain climatic characteristics. Approaches for responding to the regulatory criteria are included in the Basalt Waste Isolation Project (BWIP) issue resolution strategies given in Section 8.2.2. The primary issues requiring climate information are Issues 1.1, 1.8, 1.9(a), and 1.9(b) as discussed in Section 8.2.2. In addition, site meteorologic information is required to address Issues 2.1, 2.2, 2.3, and 2.5.

Information needs identified in the climate-related issues include (1) characterizing paleoclimate conditions during the Quaternary; (2) predicting future climate for 10,000 yr and, to a lesser extent, 100,000 yr after repository closure; and (3) modeling current meteorologic conditions for the Hanford Site. One primary purpose of assessing past and future climatic conditions is to provide information for characterizing local paleohydrology and predicting future groundwater travel. Another purpose is to predict future occurrences of glacier-related catastrophic flooding that may significantly alter the hydrologic state of the saturated rock environment of the repository. Study of climatic change over the next 100,000 yr will be used in the comparative evaluation of the three sites being considered by the U.S. Department of Energy (DOE). Assessment of current meteorologic conditions at the Hanford Site, in addition to supporting these purposes, will also be essential input for designing repository surface facilities, determining construction feasibility, scheduling operations, and developing safety programs.

The first two investigations described in this section will collect information necessary for making estimates of the effects of long-term climatic variability upon the performance of the repository. The studies supporting these investigations will characterize the long-term variability of climate at the site and forecast the nature and impact of changes within the next 100,000 yr. These changes will be characterized by specifying the climate in a number of distinct scenarios concerning (1) the climatic history of the region (paleoclimates), (2) scenarios of expected future global climates (forecasts), and (3) future local climates. These studies will

provide data for groundwater and surface water modeling studies described in Section 8.3.1.3 and will be used to assess the impact of predicted climate changes on the site groundwater flow system. Only those analyses that concern phenomena to which repository performance is sensitive will be undertaken.

Forecasts have the highest priority. The forecast models will provide input to analyses of the variability of the groundwater system due to climatic changes (see Section 8.3.1.3). The reconstruction of paleoclimates will provide a basis for understanding climatic variability (by providing reasonable limits on the magnitudes and rates of change that actually occurred) and will allow testing the models to be used for forecasts. The paleoclimate study will provide information on conditions ranging from full glacial to full interglacial conditions. Climate variability will be reconstructed at 3,000-yr time intervals starting at a time (21,000 yr ago) just before the beginning of the last glacial maximum (18,000 yr ago). Reconstructions at other times may also be done. The reconstructions will provide bases for validation of models of future climate.

The meteorologic investigation will supplement existing analyses of the meteorologic conditions of the site. An active program to monitor site meteorology, archive data, and analyze conditions has been in operation at the Hanford Site since 1945. The meteorologic investigation for the repository program will focus on improving the characterization of conditions at the proposed repository location and in the Cold Creek area, determining the spatial variability of precipitation and atmospheric moisture, and estimating atmospheric dispersion. During the period that this supplemental investigation would be carried out, the existing Hanford Site meteorologic program would continue in operation, and other meteorologic studies would be conducted to support Hanford Site activities that are unrelated to the repository project. Data from all these sources would be used to address repository-related information needs.

Background

The climatic system that influences the geologic setting for the proposed repository has been defined in Chapter 5. Paleoclimatic records of the area and procedures available for additional analyses were evaluated. These records indicate that statistically significant climatic changes have occurred within the geologic setting of the controlled area study zone during the Quaternary. On the basis of that record, it is anticipated that significant changes in the climatic system of the geologic setting will occur during the next 100,000 yr. Methods that are available to estimate future climatic conditions in the geologic setting have been discussed in Section 5.2.2. Those methods will be integrated into a set of studies that will provide the necessary paleoclimatic and future climate information to answer the issues concerning climate change (Section 8.2).

Identification of the issues relevant to the determination of climatic bounding conditions of the geohydrologic system began with a meeting of a panel of experts in January 1985. (Table 8.3.1.5-1 contains a list of the active participants.) These issues were intended to include conditions characteristic of paleoclimates of the Quaternary and climates to be expected

Table 8.3.1.5-1. Panel members for site characterization and climate change at the Hanford Site

Member	Specialty	Affiliation
Patrick J. Bartlein, Ph.D.	Paleoclimate	University of Oregon
John J. Clague, Ph.D.	Glaciation	Geological Survey of Canada
Richard G. Craig, Ph.D.	Modeling	Kent State University
Harold C. Fritts, Ph.D.	Dendroclimate	University of Arizona
Peter Mehringer, Ph.D.	Palynology	Washington State University
Nicklas Piasias, Ph.D.	Oceanography	Oregon State University
W. Geoffrey Spaulding, Ph.D.	Macrofossils	University of Washington
Richard B. Waite, Ph.D.	Paleofloods	U.S. Geological Survey

in the next 100,000 yr. The guide used at that time was the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 4.17 (NRC, 1985). Studies were identified and prioritized and a consensus reached concerning those studies to be pursued. The studies were developed into more complete study plans and were further reviewed. Further meetings were held to elaborate the plans and define appropriate schedules. The most extensive review received was commissioned by the BWIP through a contract to the Pacific Northwest Laboratory (PNL) and occurred during September 1985.

In April 1985 it became apparent to the DOE-Headquarters (DOE-HQ) that the climate studies detailed in the BWIP study plans contained significant global aspects that should be done consistently for all of the sites being considered. A meeting was held during May 1985 at DOE-HQ to discuss the directions that models of future global climate change should take. The BWIP plans were presented to representatives of the sites and national laboratories involved in site characterization. Subsequent to that meeting, a decision was made to define a single program for studies of global climate change that would produce estimates applicable to all of the sites. Through a separate contract with the PNL, the DOE is preparing those global climate change scenarios. They are described here in the interests of completeness and to show the linkages in the programs.

Considerable scientific work has been done in the Pacific Northwest to define the characteristics of and results of climate change. This work has been done over the past 100 yr and was summarized in Chapter 5. However, the record in this area is difficult to decipher due to the effects of major floods and glaciation in the area, which have tended to remove the evidence of

9 2 1 2 5 5 0 2 3 0

earlier climatic changes. Relatively few climatic studies have been completed in the Columbia Plateau using newer techniques of paleoclimatic analysis (e.g., radiocarbon dating, tephrochronology, and magnetostratigraphy). Carp Lake, located north of Goldendale, Washington, in the eastern Cascade Range, (see Fig. 5.2-8 for location) is the only site east of the Cascades that has been studied by modern techniques and shows a record that extends back through the time of the last glacial maximum. Knowledge of paleoclimatic fluctuations in sufficient detail to determine the relative stability of the groundwater system during climatic extremes is a difficult problem that has rarely been attempted and will require significant effort during site characterization.

Several studies of paleoclimatic conditions in the Columbia Plateau and of related glacially induced floods have been produced as part of the work relative to defense wastes presently stored at the Hanford Site (Craig and Singer, 1984; Singer and Craig, 1984; Craig and Hanson, 1986; Cropper and Fritts, 1986; Mehringer, 1985). Those studies and ongoing work on the long-term geologic stability of defense wastes will be of use to the BWIP during site characterization. The BWIP intends to cooperate with those scientists involved in the defense waste studies in order to minimize duplication of effort.

An extensive meteorologic monitoring program is currently in place at the Hanford Site. This program addresses the meteorologic and atmospheric dispersion data needs of the DOE and its Hanford Site contractors. In particular, the meteorology program includes the measurement, observation, and recording of meteorologic data; continuous monitoring of regional weather; and forecasting of weather conditions to site operations. Data have been used to study recent climate, prepare environmental reports, and model atmospheric dispersion. In 1944, the Hanford Meteorology Station began operation within the boundaries of the proposed geologic repository's controlled area study zone, providing around-the-clock monitoring of meteorologic parameters and data archiving. Currently, meteorologic data are collected at the station and at more than 20 associated monitoring locations within or near the Hanford Site.

Summary of program

The specific program to determine the impact of climate changes and recent meteorologic conditions at the Hanford Site is divided into three studies: (1) paleoclimatic reconstructions, (2) future climatic conditions, and (3) site meteorologic conditions. Study plans written in support of this document for site characterization will describe these studies in sufficient detail to allow evaluation of their technical promise. This will require further detail than is appropriate for this document.

In addition to the studies, system stress analyses to assess the sensitivity of the groundwater system to changes in recharge (due to climatic change) that could affect the suitability of the repository will be performed by the BWIP Performance Assessment/Systems Engineering Group. These sensitivity analyses are described in Section 8.3.1.3. Only those climate parameters to which repository performance is shown to be sensitive will be studied.

The first study, past climatic change, includes three study components: (1) reconstructing the local climate record for the Hanford Site area (Section 8.3.1.5.2.3.1), (2) summarizing the Quaternary glacial history of the Pacific Northwest (Section 8.3.1.5.2.3.2), and (3) estimating the variations in regional oceanic patterns (Section 8.3.1.5.2.3.3). Figure 8.3.1.5-1 shows the relationship of these three study components to the planned studies to predict future climate change and determine site meteorologic conditions.

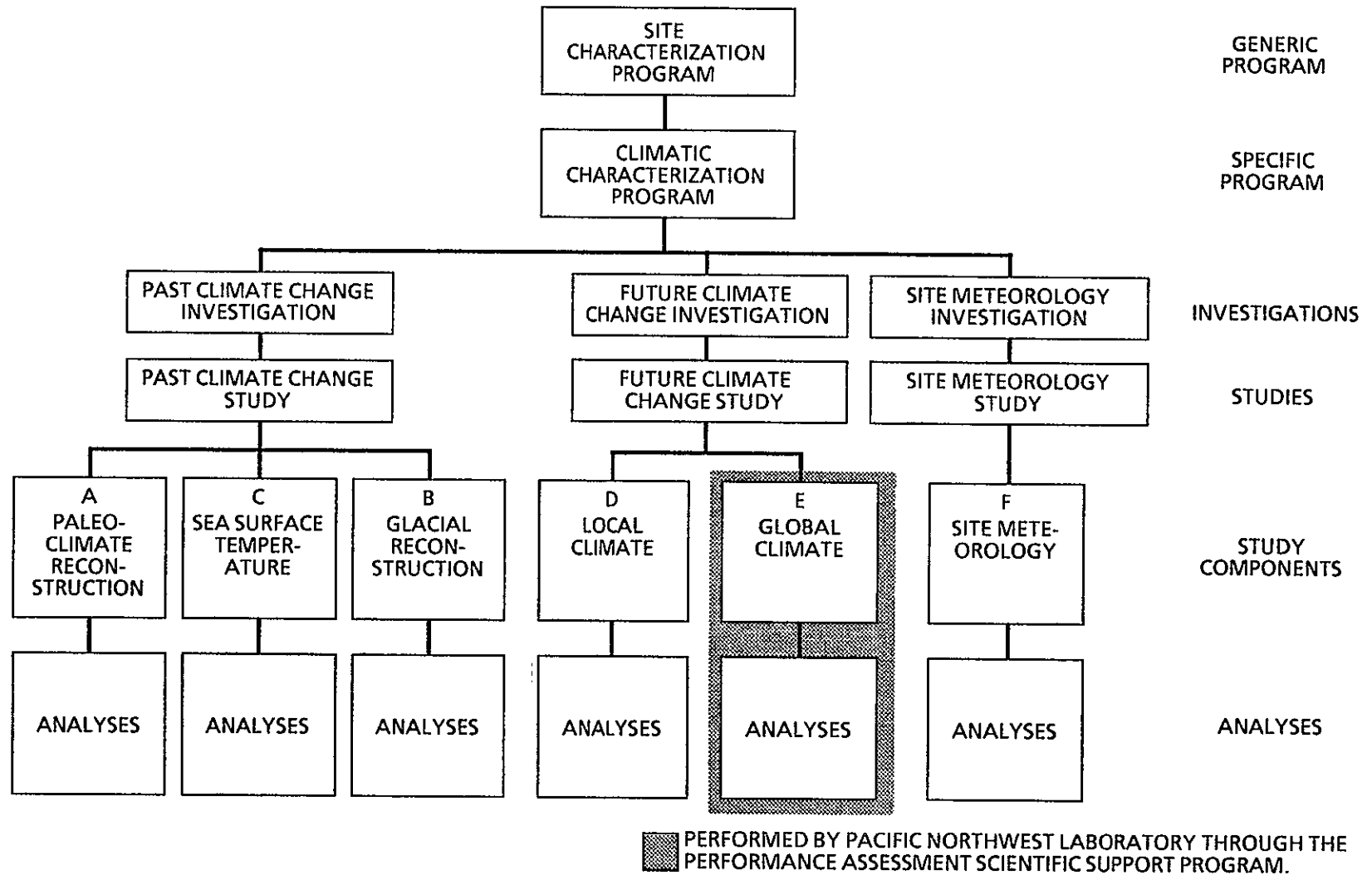
In the first study component in the past climatic change study, climatic history will be reconstructed at various times ranging from the last interglacial to the present (Study Component A). Reconstructions will be based primarily on fossil pollen preserved in lake sediments. The BWIP will study climates of times at 3,000-yr intervals, beginning before the last global glacial maximum (which occurred about 18,000 yr ago) and continuing to the present. Supplementary analyses of older deposits--back to the time of the last interglacial approximately 125,000 yr ago--will be made where such deposits can be located. No such deposits have been unequivocally recognized yet in the Columbia Plateau.

The second study component of past climatic change study will focus on the glacial history of the area (Study Component B). Such glaciations were a response to the same climatic changes that modified the temperature and precipitation patterns in the Columbia Plateau. The BWIP will study the influence of this glaciation upon the regional tectonic stress field, surface water systems, and the initiation of large magnitude floods.

The third study component of past climatic change study (Study Component C) will examine regional oceanographic controls of local climate. Surface water temperatures of the northeast Pacific Ocean influence precipitation over the area. Variations in ocean temperatures will be reconstructed from studies of fossil nannoplankton.

The second study of climate change concerns potential future changes and rates of change. This study comprises two components: (1) local climatic change (Section 8.3.1.5.3.3.1) and (2) global climatic changes that will affect the Hanford Site (Section 8.3.1.5.3.3.2) (see Fig. 8.3.1.5-1).

The first of these study components includes those analyses that will directly illustrate the local response to global climate change (Study Component D). This local response includes the local climate and the potential glaciers and floods. Estimates of local climate change will be based upon extrapolations of the current climate and climate states typical of the Late Quaternary. Linked to this local climate model will be separate computations of the hydrologic balance, including recharge, runoff, stream flow, and floods resulting from that climate. Growth of the Cordilleran ice sheet will be considered through a computer model of glacial dynamics. These models will be tested through their ability to reconstruct climates of earlier periods.



PS87-2005-8.3.1.5-1

Figure 8.3.1.5-1. Hierarchy of climatic characterization program within site characterization.

To complete the future global climate study component (Study Component E), the DOE is funding separate research activities at the PNL to develop global forecast models that can be used at all three proposed repository sites. Variations in the Earth's energy balance will be forecast by models based on the changing orbit of the Earth and other external controls. Available models will be used to evaluate the global response of the climatic system to that energy balance. The response of the global ice sheet system to this changing insolation also will be computed. Such models will describe the regional variations in the Pacific Northwest as input to the local climate model.

The estimation of rates of change is dependent upon the specification of the timespan over which the rate is to be computed. Very few paleoclimatic records afford a temporal resolution exceeding several hundred years. This will provide a limit to the application of rate-of-change information to performance assessment. For modeling studies, the majority of available models are equilibrium or steady-state descriptions. Dynamic models, such as the Milankovitch theory, are limited in their temporal resolution by the detail available in the computation of orbital parameters. Currently available solutions are a time step of 1,000 yr (Berger, 1978b). Thus, past or future rates of change cannot be estimated at the same level of precision as is available in the modern instrumental record.

The study of site meteorologic conditions comprises eight analyses, which are designed to augment the existing data base from monitoring and analysis activities conducted at the Hanford Site. These analyses will include (1) comparing of Hanford Meteorology Station data with repository site data, (2) monitoring wind in the Cold Creek syncline area, (3) assessing unanalyzed wind data from temporary monitoring stations, (4) assessing external meteorologic events, (5) tracer testing atmospheric dispersion from the proposed repository location, (6) modeling atmospheric dispersion, and (7) characterizing spatial variation in precipitation and atmospheric moisture.

Each analysis is described further in Sections 8.3.1.5.3.3, 8.3.1.5.4.3, or 8.3.1.5.5.3. The relationship between the analyses needed to estimate the effects of future climatic change and the analyses needed to estimate the growth of glaciers that could affect site stability, along with the schedules for completing these analyses, are included in Section 8.3.1.5.5.5. Many analyses provide information needed by other analyses in the same study or study component. Thus, completing these analyses on schedule will be important to ensure that results are available for site selection and licensing application.

Management of the program

The investigations of climatic changes will be managed directly by the BWIP. The meteorologic investigation will be conducted by PNL through a contractual agreement with the BWIP. Other subcontracts to various institutions will be arranged by the BWIP to use the appropriate expertise for each analysis. It is anticipated that all climate change analyses will be

performed by subcontractors according to the expertise needed. Advisory panels and review panels will be arranged by the BWIP directly. This will avoid possible conflicts of interest between the contractors and the advisors. Advisory panels will monitor the technical progress of the contract work and will judge the appropriateness of scheduled activities. There will be separate advisory panels for paleoclimatic and future climate studies because the expertise involved is so distinct. Coordination of the efforts and schedules will be facilitated by cross membership of key researchers and advisors on both panels. Coordination with the DOE global modeling study will also be achieved by representation at the various meetings of the advisory panel for that study. Finally, representatives of the climatic change program and the research group studying the regional geohydrologic system will confer on the integration of work and the status of information needs prior to each update of the Site Characterization Plan (SCP).

The BWIP management responsibilities will include the following:

- Establishing quality assurance requirements.
- Reviewing and approving quality assurance plans and procedures for individual contracts.
- Conducting quality assurance audits of contract work on a regular basis.
- Identifying needed analyses.
- Identifying appropriate contractors and letting contracts.
- Monitoring progress on contracts.
- Organizing work of the advisory panel.
- Managing efforts of review panels.

8.3.1.5.1 Purpose and objectives

This specific program for climatic characterization is designed to achieve the following:

- Satisfy requirements of the DOE in 10 CFR 960 (DOE, 1987), the NRC in 10 CFR 60 (NRC, 1987), and the U.S. Environmental Protection Agency (EPA) in 40 CFR 191 (EPA, 1986).
- Provide information for issues, parameters, and goals as identified in Section 8.2.

- Provide information to assess the effects of climate processes on the hydrology of the site, especially on the groundwater system within the controlled area study zone (see Section 8.3.1.3).
- Provide information to geologic site characterization studies, especially those concerned with tectonics and erosion (see Section 8.3.1.2).
- Evaluate climatic and meteorologic scenarios that may affect repository design, performance, constructibility, safety, and operations.

The plans presented in this section are those perceived as necessary to provide reasonable assurance to the NRC whether or not the repository will meet performance requirements for 10,000 yr specified by NRC and EPA regulations, and it will meet the goals of the DOE to remain stable over the next 100,000 yr. In addition, it is necessary to determine whether or not preclosure operations will provide adequate safety to workers and to the public. Analyses described in this section are intended to satisfy information needs identified with Issues 1.1, 1.8, 1.9(a) and 1.9(b), 2.1, 2.2, 2.3, and 2.5 (see Section 8.3.1.1).

Specific objectives through which these purposes may be achieved will include the following:

- Augment the current paleoclimate data base with data to be generated by the past climatic change study.
- Enhance understanding of site meteorology and atmospheric dispersion characteristics.
- Develop and validate climate models to be used in predicting future climate conditions.
- Project climatic variability into the future based on past climate and current meteorologic conditions.

8.3.1.5.2 Rationale

This section provides a detailed explanation of the strategy that the BWIP will use to characterize climatic changes that are likely over the next 100,000 yr or that have been observed in the geologic record of the Quaternary. It will also describe the planned strategy to augment the data base for the recent meteorology of the proposed repository site. Both strategies are built upon resolving issues discussed in Section 8.2.2.

The proposed repository at the Hanford Site would be located within the reference repository location at a depth of approximately 1 km (0.6 mi), which is within the saturated zone of the groundwater system. The site is

considered to be relatively isolated from short-term (100 to 1,000 yr) climatic effects. Potentially adverse effects that long-term climatic change (such as glaciation) could have on the stability of the repository include changes in the geohydrologic system.

Components of the geohydrologic system that could be affected by climatic change include hydraulic gradient, average interstitial velocity, and natural recharge and discharge points. Changes (particularly increases) in erosion rates could lead to removing rock mass (Ringold Formation) above the repository, which would reduce the distance to the accessible environment, although this possibility is considered unlikely based on the record of the Quaternary within the reference repository location. Extreme vertical erosion (hundreds of meters) of basalts, probably related to cataclysmic glacial-age floods from Lake Missoula, has been observed at other areas within the Columbia Plateau but not within the Pasco Basin. Regardless of the exact mechanism, the potential for adverse effects upon radionuclide isolation due to climatic change is of sufficient concern that the BWIP has designed this specific program to evaluate anticipated and unanticipated (see Glossary for the definition of these terms) climate changes.

The basis for the planned investigations of past and future climatic change is the need to resolve issues presented in Section 8.2.2. The issue resolution strategy includes performance measures, performance parameters, and tentative goals, which if met should show that repository performance meets applicable regulations. The performance parameters pertinent to climatology are linked to supporting parameters in this section. The performance parameters address bounding scenarios of recharge and evaporation for models of the regional and site groundwater system (the geohydrologic system). Such groundwater models will allow investigators to better understand the regional groundwater flow throughout the Columbia Plateau and the potential effects of that flow on waste isolation. Thus, estimates of the climatic bounding scenarios must be available throughout this area. Global climate (and by inference the climate of this area) is expected to change significantly over the next 100,000 yr (Imbrie and Imbrie, 1980). Models of climatic extremes that the area could experience in that time are required to specify appropriate bounding scenarios for the models of the groundwater system.

The basis for the planned investigation of site meteorology is the need to resolve performance and design issues presented in Section 8.2.2. Similar to climatology, the performance and design parameters corresponding to site meteorologic conditions are linked to supporting parameters given in Section 8.3.1.5.5. The performance and design parameters provide additional information to address questions on the frequency and intensity of severe weather events, requirements for the design of repository facilities, and scheduling of repository activities, characteristics of atmospheric transport and diffusion in the vicinity of the proposed repository location, and flooding and groundwater recharge. The conclusions reached using this information will help determine if the proposed repository can be safely operated at the Hanford Site.

8.3.1.5.2.1 Regulatory and issues resolution strategy rationale for the program

The DOE must comply with EPA and NRC requirements for postclosure radionuclide releases and preclosure exposure of workers and the general public to airborne radionuclide releases. The EPA requires that the DOE provide reasonable assurance that the cumulative radionuclide releases would not exceed acceptable limits during the 10,000 yr after disposal. The NRC has similarly called for the DOE to adequately investigate the likelihood that climatic changes in the 10,000 yr after disposal would not adversely affect the ability of the repository to isolate wastes. Finally, NRC licensing criteria require that the feasibility of constructing a geologic repository in basalt be established and that the radiologic safety of workers and the public be ensured during preclosure operations. The following discussion is concerned primarily with the regulatory rationale and issues resolution strategy for the investigations of past climate change and future climate change. A detailed discussion of regulatory and issues resolution strategy rationale for the meteorology is found in Section 8.3.1.5.5.2, as well as a presentation of the supporting parameters for the meteorologic elements of the radiologic safety issues (Issues 2.1, 2.2, and 2.3).

In Regulatory Guide 4.17 (NRC, 1985), the NRC has suggested a format that the DOE should follow when identifying climatic factors that could influence the stability of a repository. In addition to the information requested in Section 5.0 of that document, related concerns are discussed in the following sections of NRC (1985).

<u>Regulatory Guide 4.17 Section</u>	<u>Related concerns</u>
1.1.3	Geomorphic processes
3.2.1	Flood history (especially floods due to long-term changes in hydrometeorology or to maximum glaciation)
3.2.2	Flooding potential of the site and necessary protective measures against the effect of floods on structures at the site
3.7.4	Paleohydrology of the region (especially major past and potential flow system changes)
3.9.8	Paleohydrology of the site

The DOE is requested to provide information on climatic changes that might occur in the future based on the climatic record of the Quaternary, including consideration of the complete climatic spectrum (from maximum glacial to maximum interglacial conditions) as a minimum. The DOE is also

required to provide an assessment of the magnitude and rate of climatic changes that might be expected to occur in the future. An analysis of the Quaternary paleoclimatology will include the atmospheric, hydrospheric, and cryospheric aspects of the climatic regimes of the Quaternary. This will include analyses of changes in precipitation regimes, locations of potential aquifer recharge areas, glaciated areas, and windflow patterns. Information is also to be provided on the size of glaciers, accumulation and ablation rates, and the impact of any glaciers on precipitation regimes and windflow patterns.

In Regulatory Guide 4.17 (NRC, 1985, Section 5), the NRC requests the DOE to provide an estimate of the potential impact of future climatic variation on precipitation patterns, windflow regimes, the cryosphere, and sea levels. Long-term impact estimates are requested for the following:

- Potential maximum and minimum changes and rates of change in precipitation and air temperature.
- Potential regional windflow and precipitation patterns.
- Potential for glaciation and the times of onset of glaciation and lengths and severity of glacial regimes.
- Future fluctuations in sea level and cryosphere due to climatic changes.

The DOE has responded to the regulatory concerns of the NRC and the EPA in 10 CFR 960 (DOE, 1987). This regulation lists the process the DOE will use in selecting a repository site. Specifically, the DOE has stated that global, regional, and site climatic patterns during the Quaternary will be considered in predicting the likely future climatic conditions. The DOE will consider favorable conditions that rely upon reasonable assurance that changes in the surface water system over the next 100,000 yr will not adversely affect waste isolation. The DOE will also investigate the stability of the site during the Quaternary. Finally, the DOE will assess the stability of the geohydrologic system during the next 10,000 yr.

Issues 1.1, 1.8, 1.9(a), and 1.9(b) express postclosure concerns of the BWIP regarding the impacts of climatic change on waste stability from the viewpoints of the EPA, the NRC, and the DOE, respectively. Issues 2.1, 2.2, 2.3, and 2.5 address preclosure safety concerns about radiological exposure of workers and the general public resulting from operation, closure, and decommissioning of a repository. These preclosure concerns require assessment of recent meteorologic conditions at the site as well as more long-term climatic projections. Information needs identified to resolve those postclosure and preclosure issues are presented in Section 8.2.2. Significant information needs identified in Section 5.3 include data that will allow a determination, with reasonable assurance, as to (1) whether climatic changes in the Quaternary have had a significant effect on the hydrologic system; (2) whether future climatic conditions will be likely to lead to radionuclide releases greater than those allowable under the regulations specified in

10 CFR 960.4-1 (DOE, 1987), 10 CFR 60 (NRC, 1987), and 40 CFR 191 (EPA, 1986); and (3) whether site recent meteorologic conditions predicted from reasonable extrapolations of recent conditions will be likely to significantly affect the construction feasibility and preclosure safety of the repository.

As described in Section 8.2.2, Issue 1.1 identifies four climatic disruptive scenario classes that could produce cumulative releases of radionuclides that are greater than those allowed by 40 CFR 191 (EPA, 1986). The four disruptive scenario classes are as follows:

- Glaciation that dams the Columbia River drainage (Section 8.2.2.1.1.2.2.6).
- Glaciation over recharge and discharge areas (Section 8.2.2.1.1.2.2.7).
- Significantly increased rainfall affecting groundwater recharge (Section 8.2.2.1.1.2.2.8).
- Erosional incision that redirects the Columbia River over recharge and discharge areas (Section 8.2.2.1.1.2.2.9).

Investigation of these four disruptive scenario classes has never been attempted in a systematic way and requires the completion of a set of field investigations and modeling studies. These studies are designed to provide information that the DOE requires to assess several potentially adverse conditions (PACs) identified in 10 CFR 60.112(c) (NRC, 1987) (e.g., PAC-3, PAC-5, PAC-6, and PAC-16).

- Potentially Adverse Condition 3--Potential for natural phenomena such as landslides, subsidence, or volcanic activity of such a magnitude that large-scale surface water impoundments could be created that could change the regional groundwater flow system and thereby adversely affect the performance of the geologic repository.
- Potentially Adverse Condition 5--Potential for changes in hydrologic conditions that would affect the migration of radionuclides to the accessible environment, such as changes in hydraulic gradient, average interstitial velocity, storage coefficient, hydraulic conductivity, natural recharge, potentiometric levels, and discharge points.
- Potentially Adverse Condition 6--Potential changes in hydrologic conditions resulting from reasonably foreseeable climatic changes.
- Potentially Adverse Condition 16--Evidence of extreme erosion during the Quaternary.

The PAC-6 (hydrologic impacts of climate changes) causes the most direct concern. The regulatory and technical background for analysis of this condition is discussed in Issue 1.8 (Section 8.2.2.1.8). A tentative favorable finding on this issue in the final Environmental Assessment (DOE, 1986, Section 6.3.1.4.6) is as follows:

The climate of the Hanford Site region is not expected to change significantly over the next 10,000 yr. Thus, the groundwater flow system is expected to remain relatively unaffected.

As defined in the licensing strategy for PAC-6, sensitivity analyses will be used to determine whether climatically induced changes can be shown to affect performance parameters. Additional climatic data will be collected to refine probability estimates for any credible climate scenarios that are shown to affect performance. The studies required for this evaluation are described in this section. The performance parameter of importance in this investigation is the hydraulic gradient measured within the relevant geohydrologic system. Studies will focus upon the development of information that is required to provide a defensible estimate of changes in hydraulic gradient across the controlled area study zone in response to anticipated and unanticipated climatic changes during the next 10,000 yr. The needed paleoclimatic reconstructions and future climate models are also described in this section.

The discussion of Issue 1.9(a) (see Section 8.2.2.1.9) specifies studies that are required in order to identify anticipated and unanticipated future climatic conditions at the site in the next 10,000 yr. This information is needed to evaluate the site with respect to the qualifying condition on climatic change specified in 10 CFR 960.4-2-4 (DOE, 1987). To produce a higher level finding on this qualifying condition, the BWIP will require information about how these climatic changes could affect the hydrologic system. The analyses described in this section specify the methods that will be used to provide this information.

The BWIP intends to collect sufficient information to allow the DOE to compare the effects of climatic changes at the Hanford Site to the effects of correlative climatic changes at other sites being considered for high-level nuclear waste disposal. This comparison is required by 10 CFR 960.3-1-5 (DOE, 1987). The BWIP also intends to collect sufficient data to determine whether climatic changes or glaciation over the next 10,000 yr could induce perturbations in the hydraulic gradient, or the groundwater flux through the host rock and the surrounding geohydrologic units sufficient to increase the cumulative release of radionuclides to the accessible environment above mandated EPA limits.

The comparative analysis to be conducted in response to 10 CFR 960.3-1-5 will consider the ability of the natural barrier system to ensure compliance with the postclosure guidelines of 40 CFR 191 (EPA, 1986) and 10 CFR 60 (NRC, 1987). Issue 1.9(b) specifies the technical background of the issue resolution strategy to be followed for this comparison. The performance parameter of importance for this comparison is, as with Issue 1.8(a), the

hydraulic gradient across the controlled area study zone. Thus, the analyses that are required to resolve this issue are the same as those for Issue 1.9(a). The relationship between performance parameters and supporting parameters is shown in Table 8.3.1.5-2. The analyses, however, will be extended to allow specification of climatic change over the longer 100,000-yr timespan. This will make greater demands upon the models of climatic change that are required, since solutions are required over longer timespans. Greater levels of uncertainty will probably be involved and special care will have to be taken for more extensive testing before these longer forecasts are made. Measures of uncertainty will be produced during the modeling study for the comparative evaluations. It is not known if the uncertainty associated with either of these prediction intervals will be acceptable to the NRC.

Table 8.3.1.5-2 shows five performance parameters that are planned to be estimated in the climate change program. The first of these, hydraulic gradient across the controlled area study zone, derives from studies defined in Section 8.3.1.3. The other four derive from Issue 1.9(b). Estimation of the values of each of the five performance parameters requires information about several supporting parameters. In many cases, the same supporting parameters are required for more than one performance parameter. Where probabilities are called for, the current estimate column may include two values. In that case, the first value will refer to the current estimate of the probability of that event in the next 10,000 yr. The second value refers to the probability of that event in the next 100,000 yr. In all cases the value given is either 0.5 or 1.0. The first of these, 0.5, is used to indicate that there is absolute uncertainty about this point at this time. The value, 0.5, indicates, therefore, equal chance of either outcome to the best of our knowledge. The second of these, 1.0, indicates that it is nearly certain that the event will occur, although there are not defensible data to support that statement now, as indicated in the low current confidences.

In all cases in Table 8.3.1.5-2, it is assumed that the needed confidence is very high, greater than 0.99. This confidence is needed to allow determination of the disruptive scenarios that have a cumulative probability of 0.0001 or greater in 10,000 yr. At the present time, this is the level of resolution of disruptive scenarios that is required by the DOE guidelines and definitions of anticipated and unanticipated events (see Glossary).

More detailed information is provided in Table 8.3.1.5-3 for the supporting parameters given in Table 8.3.1.5-2 requiring characterization. The contents of the current data representation column are inserted to illustrate the current knowledge of the kinds of information that will be produced during site characterization. For example, the frequency distribution of temperature is assumed to be the normal distribution. We assume that this will have some mean, x , and variance, v . The values of these parameters must be estimated during site characterization. In general, these parameters will vary as a function of both space and time during the period of concern. Thus, it is impractical to specify values.

Table 8.3.1.5-2. Supporting parameters for performance parameters derived from Issues 1.1, 1.8, and 1.9(b) (sheet 1 of 2)

System element; performance measure	Performance parameter	Supporting parameter	Current estimate	Confidence		Other SCP sections
				Current	Needed	
Site subsystem; cumulative release at the accessible environment, $m = (C_i/C_{i\text{allowable}})$	Hydraulic gradient across controlled area study zone	Hydraulic gradient in surrounding region	1×10^{-3} to 1×10^{-5}	Medium	Very high	8.3.1.3
		Recharge rate	< 10 mm/yr	Low	Very high	8.3.1.3
		Climatic parameters related to recharge	Characterization #1 (see Table 8.3.1.5-3)	Low	Very high	
	Probability of occurrence of glaciation that dams Columbia River drainage (Scenario 1)	Conditional probability of floods given glaciation and ice dam	0.5/1.0 ^b	Low/medium ^b	Very high	
		Conditional probability of floods given glaciation and ice dam	0.5/1.0 ^b	Low/medium ^b	Very high	
		Conditional probability of ice dam given glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
		Probability of glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
	Probability of occurrence of glaciation over recharge and discharge areas (Scenario 2)	Conditional probability of area being covered given glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
		Conditional probability of lake given glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
		Probability of glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
	Probability of occurrence of significantly increased rainfall (Scenario 3)	Climatic parameters related to precipitation	Characterization #2 (see Table 8.3.1.5-3)	Low	Very high	
	Probability of occurrence of significant erosional incision of Columbia River (Scenario 4)	Probability of a drop in base level given glaciation	0.5/1.0 ^b	Low	Very high	
		Probability of glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	

PST88-2014-8.3.1.5-1

Table 8.3.1.5-2. Supporting parameters for performance parameters derived from Issues 1.1, 1.8, and 1.9(b) (sheet 2 of 2)

System element; performance measure	Performance parameter	Supporting parameter	Current estimate	Confidence		Other SCP sections
				Current	Needed	
Site subsystem; cumulative release at the accessible environment, $m = (C_i/C_{i,allowable})$ (cont.)	Probability of occurrence of significant erosional incision of Columbia River (Scenario 4) (cont.)	Conditional probability of floods given glaciation and ice dam	0.5/1.0 ^b	Low/medium ^b	Very high	
		Conditional probability of ice dam given glaciation	0.5/1.0 ^b	Low/medium ^b	Very high	
		Climatic parameters related to floods and glaciation	Characterization #3 (see Table 8.3.1.5-3)	Low	Very high	

^aVery high = >99%.

High = >90%.

Medium = >50%.

Low = <50%.

^bEstimates of probability and current confidences with two values given are for the 10,000-yr and 100,000 yr periods, respectively High = >90%, Medium = >50%, and Low = <50%.

PST88-2014-8.3.1.5-1

Table 8.3.1.5-3. Data requirements for certain climate-related supporting parameters

Relevant supporting parameters ^a	Data requirements	Current data representation ^b
Climatic parameters related to recharge (Characterization #1) Climatic parameters related to precipitation (Characterization #2)	Frequency distributions of: Precipitation Temperature Evapotranspiration Vegetation: Type Density Soils: Type Depth	CN (x, v) N (x, v) N (x, v) fn (cl) fn (cl) fn (br, cl) fn (br, cl)
Climatic parameters related to recharge (Characterization #1) Climatic parameters related to floods and glaciation (Characterization #3)	Frequency distribution of flood: Depth Duration Erosion Deposition Transport	N (x, v) N (x, v) N (x, v) N (x, v) N (x, v)
Climatic parameters related to precipitation (Characterization #1) Climatic parameters related to recharge (Characterization #2) Climatic parameters related to floods and glaciation (Characterization #3)	Boundary conditions: Topography Global: Ice volume Sea level Isostatics Airflow Sea surface temperature	DEM fn (orb, o) fn (i, iso) fn (i, l, e) fn (eb, bc) fn (eb, bc)

^aRelationships between supporting parameters and performance parameters are given in Table 8.3.1.5-2.

^bAbbreviations:

- bc = Boundary conditions such as topography, land and ice cover, etc.
- br = Bedrock type.
- cl = Climate.
- CN = Cube root is distributed normally.
- DEM = Digital elevation model.
- e = Earth geophysical parameters (strength, etc.).
- eb = Energy balance.
- fn = Function of parameters shown in parentheses.
- i = Ice sheet volume.
- iso = Isostatic effects.
- l = Lag effects in isostatic rebound due to rheidity.
- N = Normal distribution.
- orb = Orbital parameters.
- o = Other influences on climate.
- x = Mean.
- v = Variance.

PST88-2014-8.3.1.5-2

Where more appropriate, the current data representation column in Table 8.3.1.5-3 presents relational statements to indicate that the distribution form is a function of other controlling parameters. For example, we expect that vegetation type is a function of climate. Thus, the vegetation type is a function of space and time (assumed for all of these frequency distributions) as well as climate. Therefore, specification of this parameter can only be provided from sophisticated computer programs.

With respect to specific performance parameters and the supporting parameters needed to calculate them (Table 8.3.1.5-2), we have suggested that the first is considered as an estimate of the actual value of hydraulic gradient. In order to estimate this value at all times in the next 10,000 yr, the actual values of recharge and the factors controlling recharge must be specified. Since the values of the controlling factors vary at the different locations that are of concern in these computations, it is necessary to provide those supporting parameter values as frequency distributions in most cases (see Table 8.3.1.5-3). In the case of precipitation, temperature, and evapotranspiration, the appropriate forms of these frequency distributions are suggested. These are for illustrative purposes only. It will be necessary to examine each of these more carefully before a final frequency distribution is selected.

Since the performance parameter of hydraulic gradient may be affected by flood-derived recharge, the data needed to compute that recharge are also listed. Again, although frequency distributions may be used to report these values we have little confidence in the current estimate of their form and we have no useful information about the specific values that can be reported at this time. Future updates may be improved by consideration of available data.

Finally, for computation of the first performance parameter (e.g., hydraulic gradient), the boundary conditions listed in Table 8.3.1.5-3 must be specified. These include the items listed. This list is an abbreviated one; the items listed are shorthand notations for much more complicated ideas. For example, "airflow" means that the global atmospheric circulation patterns must be solved and specified at grid cells in the area surrounding the site. These form boundary conditions for local models of winds that, in turn, will form the basis of estimates of other climatic variables. The process is a complicated one and is described later in Section 8.3.1.5 and Chapter 5.

The second performance parameter in Table 8.3.1.5-2 is a probability, the probability of disruption of the groundwater of disruption of the groundwater system due to major floods. These floods have occurred in the past and are considered likely in the future. They are of two types: those derived from Lake Bonneville via the Snake River and those from Lake Missoula via the Scablands. To produce either of these floods requires establishment of certain values of supporting parameters. We represent the relations of the controlling supporting parameters in this case by the use of a conditional probability. For the Missoula Floods to occur, glaciation must have occurred and must have created an ice dam. Only certain glacial conditions will result in an ice dam, so there is a further conditional probability on this phenomenon. Finally we must consider the probability of glaciation itself.

Each of these probabilities derives from a complex set of additional considerations. Some of these have already been described in Section 8.3.1.5 and Chapter 5. Additional detail will be provided in the study plans.

Similar logic is used to develop the entries in the rows relating to the probability of scenario 2 in Table 8.3.1.5-2. In this case, we must determine the probability that a glaciation will affect discharge or recharge areas of the groundwater system. That probability is conditional upon the occurrence of glaciation. Another disruption resulting from glaciation is the formation of lakes that can impact the discharge/recharge relations in the groundwater system. This is described with a separate conditional probability.

The fourth performance parameter (probability of scenario 3 in Table 8.3.1.5-2) can be estimated with information that is also required to compute the recharge estimates for the first performance parameter. This will not be discussed further here.

The fifth performance parameter (probability of scenario 4 in Table 8.3.1.5-2) also makes use of information required for the first performance parameter (see Table 8.3.1.5-3). It also requires additional information. Incision can arise from two sources: major floods and lowering of sea level. The probability of the first of these can be estimated from the frequency distributions and boundary conditions that are needed for estimation of the first performance parameter. The second of these, sea level lowering, can be estimated from a conditional probability approach similar to that used for several other performance parameters. The probability of incision can be computed in that case from the probability of a drop in base level given glaciation and the probability of glaciation. The latter probability must be known for two other performance parameter probability calculations.

Recent meteorology, atmospheric dispersion, and related information are required to address the radiological safety issues (Issues 2.1, 2.2, 2.3, and 2.5) identified in Section 8.2.2. These issues were derived from 10 CFR 960, 10 CFR 60, and 40 CFR 191. Pertinent sections of these regulations and the issues that involve a consideration of meteorology and atmospheric dispersion are summarized in Section 8.3.1.5.5.2, as well as the supporting parameters for the meteorologic elements of Issue 2.1, 2.2, and 2.3.

8.3.1.5.2.2 Technical rationale for the program

To determine if the potential climatic changes are likely to lead to significant releases of radionuclides, the BWIP will investigate paleoclimates and will model future climates that are anticipated (i.e., cumulative probability greater than 0.1, see also glossary) in the next 10,000 yr (Issues 1.1, 1.8, 1.9(a)). The BWIP will also consider events and processes that are unanticipated (i.e., cumulative probability less than 0.1 but greater than 0.0001 in the 10,000-yr period, see also Glossary) in the next 100,000 yr (Issue 1.9(b)). Analyses of paleoclimatic evidence will provide estimates of rates and magnitudes of changes that have occurred in the Quaternary. Emphasis will be placed upon the Late Quaternary (the last 0.125 m.y.) because of the limitations of the geologic record. Reconstructions of paleoclimates at specific time periods will also form the bases for the validation of models

of climate. Such tests will provide estimates of uncertainty in forecasts of future climatic conditions. Both the model forecasts and the measures of uncertainty will be reported.

Twenty-nine major analyses will be conducted in support of the three climatologic and meteorologic investigations to be conducted during site characterization. Table 8.3.1.5-4 summarizes the study components. Fifteen of these analyses are part of the investigation of paleoclimates of the Pacific Northwest. The objectives of these analyses are stated in Section 8.3.1.5.3. Six analyses will produce models of climate change anticipated in the next 100,000 yr. The objectives of these analyses are described in Section 8.3.1.5.4. Eight analyses will be conducted to address concerns about recent meteorology and atmospheric dispersion. The objectives of these analyses are described in Section 8.3.1.5.5.

Because of the broad change of analyses required and the resultant large number of scientists involved, special efforts will be needed to ensure that the analyses are coordinated. Three advisory panels (one for each investigation) will be established by the BWIP to monitor progress and recommend research strategies as the work progresses. As analysis milestones are reached, the advisory panels will commission review groups to certify successful completion of goals.

Current plans call for each of these advisory panels to consist of six to twelve members. They will include researchers actually involved in the various analyses and independent experts in the same or similar fields who have been actively engaged in the same types of research. Examples of the expertise expected to be included in the advisory panels are provided in Table 8.3.1.5-5. The advisory panels will be expected to meet regularly, at approximately 6-mo intervals. These meetings will be arranged to review the progress on the studies before the regular 6-mo updates to the SCP are issued.

The principal objective of the paleoclimate analyses (Study Components A, B, and C) will be to reconstruct paleoclimates at specified times during the Late Quaternary. These reconstructions will be used to allow evaluation of the sensitivity of the groundwater system. Paleoclimate reconstructions also allow tests of the models to be used to forecast future climates. Ongoing paleoclimatic research independent of the BWIP is now reconstructing paleoclimates at 3,000-yr intervals during the Late Quaternary (Kerr, 1984). Information for the period 6,000 B.P. is now available (Webb, 1985). To take advantage of this work--because it is the most likely period to yield information at this level of detail--and to ensure that the results are available in a timely manner, the BWIP has chosen the same 3,000-yr intervals of time for paleoclimatic reconstructions. These reconstructions will extend to 21,000 yr ago. The availability of this information will allow estimates of the magnitude and rates of climatic change as discussed in Regulatory Guide 4.17 (NRC, 1985).

Table 8.3.1.5-4. Studies and study components included in the specific program for investigation of the impact of climatic changes

SCP section	Study component	Title	Abbreviated description
8.3.1.5.3.3.1	A	Characterization of local paleoclimates for the Hanford Site area	Local climate at various time of the Late Quaternary will be reconstructed using fossil pollen data from lake sediments. The pollen data will be calibrated to climate through transfer functions. The standard climate will be reconstructed from dendroclimatic data
8.3.1.5.3.3.2	B	Quaternary history of glaciation in the Pacific Northwest	Stratigraphic methods will be used to supplement the existing information about the glaciation where gaps exist. Field mapping will be used to characterize the dynamics of the ice sheet, effects of the ice on the major rivers, and behavior of the large floods. The disruption of groundwater by flood water incursion will be studied using hydrogeological techniques
8.3.1.5.3.3.3	C	Climatic history of the northeast Pacific Ocean	Atmospheric variations will be estimated using atmospheric general circulation models, which are used for climatic forecasts. The results of this analysis, required as input to the local climate model, will be tested against the paleobiotic-based reconstructions for the region
8.3.1.5.4.3.1	D	Projection of local climate change	The local climate model will characterize future climates directly. Results of the study will be used to specify the boundary conditions to allow modeling of future groundwater systems and specify external controls on the growth of the Cordilleran Ice Sheet at its southern margin
8.3.1.5.4.3.2	E	Future global climate change	The local climate model will represent the influences of the global climate state, including such factors as oceanic circulation patterns and the regional ice sheet
8.3.1.5.5.3	F	Site meteorology	Additional meteorological data will be collected to supplement the existing data base. Meteorological conditions in the area of the Cold Creek Valley will be examined in greater detail. Field experiments and computer simulations will be conducted to increase our knowledge of local atmospheric dispersion characteristics

PST88-2014-8.3.1.5-3

Table 8.3.1.5-5. Expertise to be included in the advisory panels for climate change studies

Paleoclimate panel	Future climate panel
Dendroclimatology	Local climate modeling
Palynology	Hydrology
Limmology	Glaciology
Geochemistry	Global circulation model
Geochronology	Milankovitch
Tephrochronology	Atmospheric sciences
Loess	Oceanography
Pollen/climate transfer function	
General paneoclimatology	
Oceanography	
Hydrology	
Glaciology	

The paleoclimatic reconstructions will serve a second purpose of validating the models (in the sense of NUREG-0856 as discussed in Silling, 1983) to be used for forecasts of future climates. Models of local climate to be produced will provide detailed estimates of climatic conditions in a geographic grid throughout the geologic setting of the repository. They will be constructed to allow solutions also at the times in the geologic past for which the BWIP is reconstructing paleoclimates. Model solutions will be compared to paleoclimatic reconstructions to validate the model and data produced. Forecasts of future climates with the models will not be attempted until the validation tests are considered acceptable by the advisory panel and external peer review.

Future climatic variation will be modeled with a set of six models (Section 8.3.1.5.3.1). Three will estimate the local components of the climatic variation, which are climate, glaciers and floods (Study Component D). The other three will describe the global controls upon the climatic system, which include global circulation systems and global energy balance (Study Component E). The local models will use the results of the global models as boundary conditions. Climatic fluctuations that could significantly affect the repository will almost surely be global in extent. The probability and timing of local climatic variations can only be estimated by models that recognize the global controls. Such models will also provide a representation of the effect of local changes in vegetation and terrain (e.g., glaciation on local climate).

Global climatic changes may significantly affect all sites now being considered as repositories for nuclear waste. All sites must evaluate the global controls upon climatic change. If the site studies do not all make use of the same modeling assumptions about global climatic change, decisions about the stability of a site might be unduly influenced by the modeling scheme used rather than reflecting the actual conditions. Consistency among the sites in

the assumptions about global climate change is essential for valid comparisons. The DOE has recognized this and initiated a study at the PNL for providing models of global climate change that will be available for use by all of the sites. These DOE models will be used by the BWIP to assess the stability of the geohydrologic system following local climatic changes. A description of the global analyses funded by the DOE-HQ is included (Section 8.3.1.5.3.2) to clarify the way in which the BWIP intends to use this information during the characterization of the Hanford Site.

Climatic models to characterize anticipated future climates will identify and specify scenarios rather than attempting to compute the entire sequence of climatic states of the next 100,000 yr. Such a modeling exercise would not be possible given the current state of climatic modeling and computer technology. It would also be wasteful of resources; only climatic extremes considered likely to significantly impact site stability (in the sense of leading to radionuclide releases exceeding the levels established in 40 CFR 191 (EPA, 1986)) need be considered. Climatic states representing extremes in the global climatic system of sufficient magnitude to affect the regional climatic system will be identified (Section 8.3.1.5.3). Boundary conditions representing the regional influence of these global climatic states will be established and local climate models will be run under those boundary conditions. These climatic scenarios will allow computation of recharge and that information will be passed to models of the regional geohydrologic system to assess its stability.

Site meteorologic analyses will gather site specific data on the representativeness of data at the Hanford Meteorologic Station for the proposed repository location, winds at key locations, atmospheric dispersion characteristics, and the spatial variation in precipitation and atmospheric moisture. Assessments will be made of data on severe meteorologic events and atmospheric dispersion will be simulated by computer models. These analyses will supplement information from the ongoing Hanford Site meteorology program and from other meteorologic studies that are unrelated to the repository program. All available data and analyses will be used to assess the feasibility of constructing a geologic repository for the proposed site, designing repository facilities, and scheduling site operations. Meteorologic data will also play a critical role in developing plans to assure preclosure radiologic safety of site workers and the general public.

8.3.1.5.3 Past climatic change investigation

This section provides a more detailed discussion of the analyses intended for paleoclimatic reconstructions. Included is a discussion of the relation of the analyses to the issues involving climate change, an outline of the potential impact of climate change on the site, and an explanation of how site characterization will resolve the issues involving climate change. There are three study components: (A) paleoclimate reconstructions, (B) glacial reconstructions, and (C) sea surface temperature reconstructions (see Fig. 8.3.1.5-1).

The paleoclimate study will include eight analyses (Study Component A) to produce direct evidence about the paleoclimatic characteristics of the geologic setting at various times during the Quaternary (Fig. 8.3.1.5-2). Existing paleoclimatic information will be summarized (Analysis A1) and new data collected in several independent analyses (Analyses A2 through A7). All of this information will be synthesized into a consistent description of paleoclimatic changes (Analysis A8). The paleoclimatic characteristics will be reported as a set of maps of climatic variables (e.g., precipitation and temperature) representing various times in the late Quaternary.

Available published literature will form the basis for developing a systematic understanding of the magnitude and rate of climatic change in the Quaternary (Analysis A1). Information will be collected and synthesized to obtain a usable description of past climatic conditions in the geologic setting of the repository. Because of the disparate views and varying quality of work reported in the literature, a working group of scientists involved in the program will review the literature to determine the interpretations to be applied in each case. If resolution of interpretations cannot be achieved, the existence of multiple theoretical bases will be formally recognized, and strategies to identify their importance will be formulated. Detailed procedures for this will be defined in the study plans.

The first group of analyses in Study Component A will provide paleoclimatic reconstructions using biotic data from two independent methods. The primary tool will be fossil pollen preserved in lake sediments at locations within the geologic setting (Analysis A4). Transfer functions will be used to estimate climatic parameters from abundances of various fossil pollen species (Analysis A3). The second paleobiotic method will make use of fossil diatoms (or possibly ostracods or cladocera) to be extracted from the same lake sediment cores used to obtain the pollen (Analysis A5). These will be used to reconstruct paleoclimates at the times that the fossils were deposited. The availability of this second data set will allow measures of consistency; if one method fails to provide sufficient data, the second method will act as a backup.

A second group of paleoclimatic analyses in Study Component A will emphasize longer term (but lower resolution) records that extend throughout the Quaternary and beyond. Deposits of windblown silt (loess) and other eolian deposits will be studied at various locations throughout the geologic setting (Analysis A7). It is anticipated that these deposits will provide evidence of the magnitudes and timing of major fluctuations in atmospheric circulation and local paleoclimates throughout the Quaternary.

The history of sea surface temperature changes in the northeast Pacific Ocean throughout a significant portion of the Quaternary will be reconstructed using fossils of planktonic species retrieved from cores of oceanic sediments (Analysis C1). This will provide a second means of estimating long-term climatic variation in the Pacific Northwest. Analysis C2 will provide reconstructions of sea surface temperatures in the northeastern Pacific Ocean at the same time periods studied in Analysis A8.

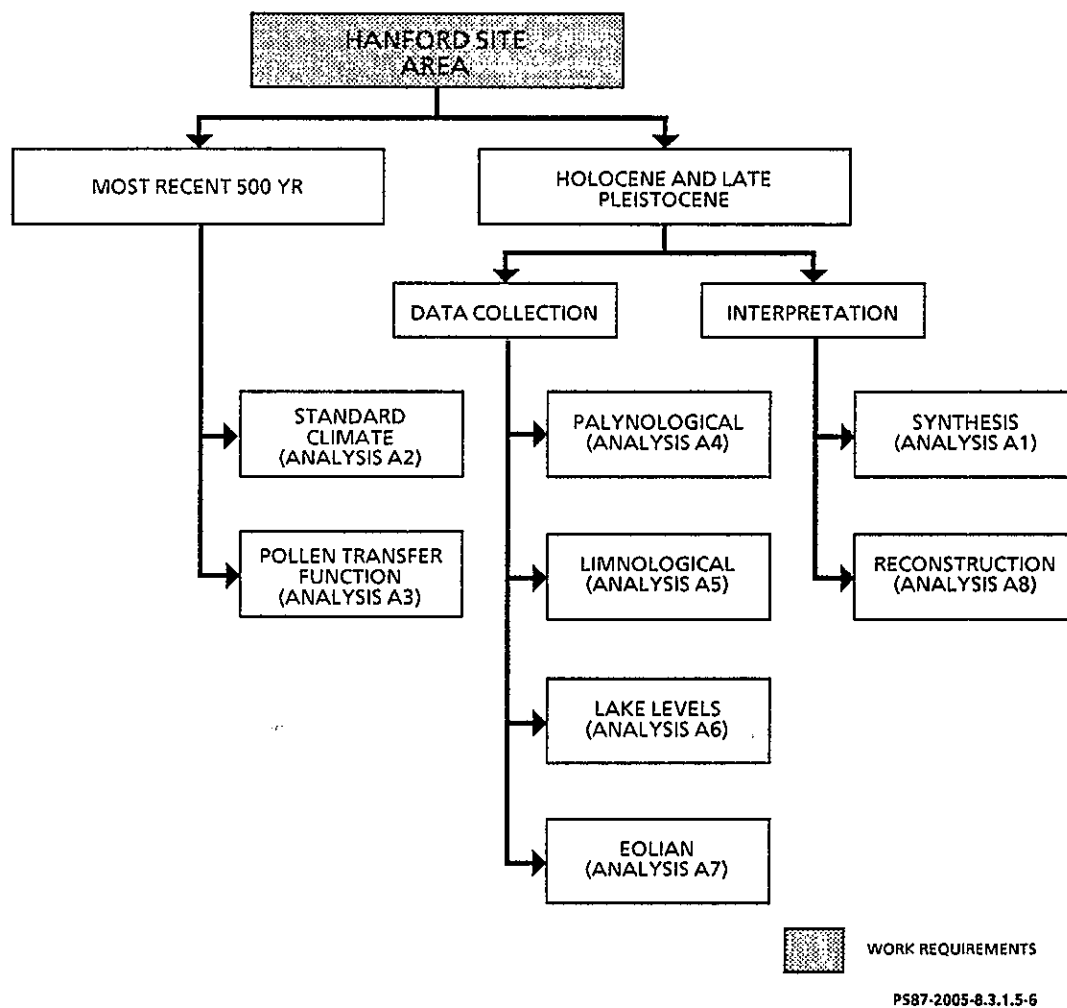


Figure 8.3.1.5-2. Work requirements and analyses included in the characterization of paleoclimates.

Because the most extreme changes in the past are believed to be those accompanying major glaciation events, such glaciation will be characterized in five separate analyses. The configuration of the southern margin of the Cordilleran Ice Sheet in the Late Quaternary will be reconstructed in maps (Analysis B1). The dynamic behavior of that ice sheet during its growth and decay will also be illustrated on those maps, and the effects of that ice sheet on the tectonic regime of the geologic setting will be estimated (Analysis B2). The direct and indirect disruptions of the surface-water system as a result of glaciation will be characterized from field evidence (Analysis B3). Past glaciations have produced enormous floods in the Pasco Basin, and the field evidence concerning the dynamics of such floods will be summarized (Analysis B4). The actual effects of past floods on the groundwater system will be examined in detail (Analysis B5).

Two analyses will characterize the history of the northeast Pacific Ocean during the Quaternary. Analysis C1 will look in detail at the variations at one point over the entire period. Analysis C2 will characterize the variability of sea surface temperatures throughout the northeast Pacific Ocean at each of several time periods.

8.3.1.5.3.1 Purpose and objectives of investigation

The following section provides a brief description of the information that will be obtained in this investigation and how the information will be used. Also included is the rationale and justification for the information to be obtained by the investigation. In general, the rationale for these investigations derives from direct Federal regulatory requirements for specific studies. Where these apply to the objectives of other investigations, the relationships between this investigation and the higher level goals are described. Paleoclimate studies are planned for two purposes. One is to augment paleohydrological groundwater characterization by providing estimates of paleorecharge in other climatic regimes. The other is to develop and validate climate models to be used in predicting future climate conditions as input to predicting radionuclide travel in groundwater primarily by providing estimates of recharge for the next 10,000 yr.

At this time it is not known whether the precision and accuracy of the data to be collected is likely to satisfy the requirements of the methods that will be used to predict radionuclide transport. Those methods themselves have not yet been completely defined. Table 8.3.1.3-7, Section 8.3.1.3, lists those parameters that are needed for the hydrologic modeling. Studies described in Section 8.3.1.3 will provide information about the resolution in these parameters that will be required. When that information is available, the climate studies will be reevaluated to determine whether the climate change research effort will provide an adequate level of detail. Redirection of the study plans may be necessary at that time. The paleoclimate study is divided into 16 analyses, which are described in this section.

8.3.1.5.3.2 Rationale for investigation

The characterization of climates that the region has experienced during the Quaternary (Heusser, 1983; Mehringer, 1985; Porter et al., 1983) must rely almost exclusively on geologic evidence, which is sparse and incomplete. To provide reconstructions of the greatest reliability, a range of different techniques will be applied, as appropriate.

Descriptions of paleoclimates of the local area will be based on the fossil record of proxy climate indicators. Cores of lake sediments can yield pollen characteristic of the climate at the time the sediment was deposited (Faegri and Iversen, 1975; Birks and Birks, 1980). Age of the sediments is determined through radiocarbon dating (Sheppard, 1975), paleomagnetism, thermoluminescence, Uranium-series, fission track, and tephrochronology (Sarna-Wojcicki et al., 1983). The relation between the vegetation represented by fossil pollen spectra and the actual climate at that time can be computed from pollen/climate transfer functions (Howe and Webb, 1983; Bartlein et al., 1984).

Pollen and climate transfer functions must be constructed from pollen abundances typical of the presettlement period (100 to 500 yr ago). Modern pollen rain is not typical of that period, because of the landscape alteration and introduction of exotic plant species that accompanied European settlement (Mack and Bryant, 1974; Heusser, 1978). The BWIP will sample pollen from sediment deposited between 100 and 500 yr ago in lakes located in representative vegetation and climate zones. Climate for the period 100 to 500 yr ago will be reconstructed using tree-ring records (Fritts, 1976; 1985). These pollen and climate reconstructions will be related through transfer functions.

During the Quaternary glacial ages, great ice sheets extended into northern Washington (see Section 5.2.1.2.3). The ice impacted the rivers and local climate (Waite and Thorson, 1983; Porter et al., 1983). The history of the Cordilleran Ice Sheet lobes in eastern Washington, as well as alpine glaciers in the Cascade Range, will be summarized. These summaries will be based on the relevant literature and additional field work as required. Attention will be focused on the glacial history of the last (Wisconsinan) glaciation, which is the best known.

Separate analysis of the dynamic behavior of ice sheets in the region will allow testing models of future glaciers. One influence of glaciation was the modification of surface drainage systems. Major floods, the most extensive known from the geologic record, probably accompanied each major glacial advance. Flood waters directly covered the reference repository location during the last series of events (Baker and Bunker, 1985; Waite, 1980), and an examination of the effects of these floods will be a separate analysis item. The possibility that such floods can influence the groundwater system will also be investigated.

The climate of the Pasco Basin is strongly influenced by the Pacific Ocean (see Section 5.2.1.3). Prevailing westerly winds carry precipitable water inland. The strong orographic influence of the Cascade Range results in undersaturated air reaching the Hanford Site. Thus, it is the combination of the amount of moisture provided by the Pacific Ocean, orientation of the dominant wind fields, and topographic setting of the region that defines the climatology of the area. An examination of the temperature history of the northeast Pacific Ocean will be made to place the reconstructed climate in the appropriate regional context and ensure that mechanisms of climate change are correctly understood before forecasts are made.

The amount of moisture supplied by the Pacific Ocean is influenced by the rate of evaporation from its surface. This, in turn, is controlled by the temperature of the water at the ocean-atmosphere interface (i.e., the sea surface temperature). Reconstruction of sea surface temperatures will be accomplished using methods analogous to the pollen-based climate reconstructions on land (Ruddiman, 1985). Fossil planktonic species obtained from specified temporal horizons in deep-sea cores will be employed.

Transfer functions relate the abundance of different species (or suites of species) to the sea surface temperature. These will be used to reconstruct regional sea surface temperature patterns in the northeast Pacific Ocean at regular time "slices" in the late Quaternary. Also, the continuous temporal history of sea surface temperatures will be summarized at one location to characterize its relationship to sea surface temperatures occurring on a more global scale. Only a single location is to be studied because the record is unlikely to be found in many cores and the time required to obtain additional cores would probably be prohibitive. It is now standard practice in paleo-oceanographic studies to represent large areas of the ocean with results of single cores. For example, the CLIMAP (1981) global reconstructions used 450 cores throughout the world's oceans. Ruddiman (1985) discusses many examples of paleoclimatic reconstructions from oceanic core records.

Atmospheric circulation establishes the local pattern of climate, and it can change because of variations in the global ocean circulation (see Section 5.2.2.3). Massive ice sheets further perturb circulation patterns. Both types of changes occurred in this area; large glaciers were near and sea-surface temperature patterns had shifted (Gates, 1976). These changes constitute the cryosphere-atmosphere-ocean system, and the effects on atmospheric circulation must be understood. Minimal geologic data are available so computer models will be used. Models are available that have been used for similar problems already (Manabe and Broccoli, 1984).

The various study components for characterizing the paleoclimates of the Pasco Basin are identified in Figure 8.3.1.5-1. The relative order in which the work must progress due to interdependence between different items is discussed in Section 8.3.1.5.3.5. Although most of the analyses can proceed relatively independently, certain critical relationships must be satisfied. These are discussed in the following paragraphs.

Climatic reconstructions for the late Quaternary (Analysis A8) cannot be completed until the transfer functions are available (Analysis A3). These must be based on dendroclimatic reconstructions for the period 100 to 500 yr ago (Analysis A2). The long-term climatic reconstructions also require several cores with records extending through at least the last glacial maximum from different lakes in the area (Analysis A4). Only one such core is presently available from the Columbia Plateau (Barnosky, 1985).

Reconstruction of local atmospheric circulation patterns is based on the specification of boundary conditions. These include the configuration of the Cordilleran Ice Sheet (Analysis B1) and the pattern of sea surface temperatures in the northeast Pacific Ocean (Analysis C1). Atmospheric modeling can be conducted for a specific time horizon (e.g., 15,000 yr ago) as soon as the glacier and ocean information are available for that horizon. If carefully coordinated, much of this work can proceed concurrently. This is important since each item of the cryosphere-atmosphere-ocean reconstructions will require several years of work.

8.3.1.5.3.3 Description of past climatic change study

Three study components will be executed by the BWIP to define the paleoclimatic characteristics of the Quaternary within the geologic setting of the repository. These studies will identify the local paleoclimates, variations in the cryosphere, and changes in the oceanic systems bordering the coast of Washington State. This information will be used to assess the stability of the geohydrologic system during the Quaternary.

8.3.1.5.3.3.1 Study Component A: characterization of local paleoclimates for the Hanford Site area.

This study component will reconstruct the local climate at various times in the late Quaternary using fossil pollen data from lake sediments. The pollen data will be calibrated to climate using transfer functions developed by relating subrecent pollen abundances to a standard climate for the Columbia Plateau. The standard climate will be reconstructed from dendroclimatic data of the past 400 to 500 yr and weather station data.

These items are all grouped into a single study component because they all derive from the same requirement; i.e., 10 CFR 960 calls for an assessment of Quaternary climates (DOE, 1987, pp. 47761-47762). In addition, these analyses are interrelated in that the data derived from one may form the input to another, or the results of the first will calibrate, or test, the results of another. The relationships between these various studies are shown in Figure 8.3.1.5-3.

For the local climate reconstructions, pollen spectra from cores extending through at least the last glacial maximum of a number of lakes can be obtained immediately. These cores cannot be interpreted in paleoclimatic terms until a transfer function is available. For the transfer functions, the dendroclimatic reconstructions and the core-top samples of pollen must be available. Thus, the dendroclimatic reconstructions and core-top sampling must be done at an earlier date.

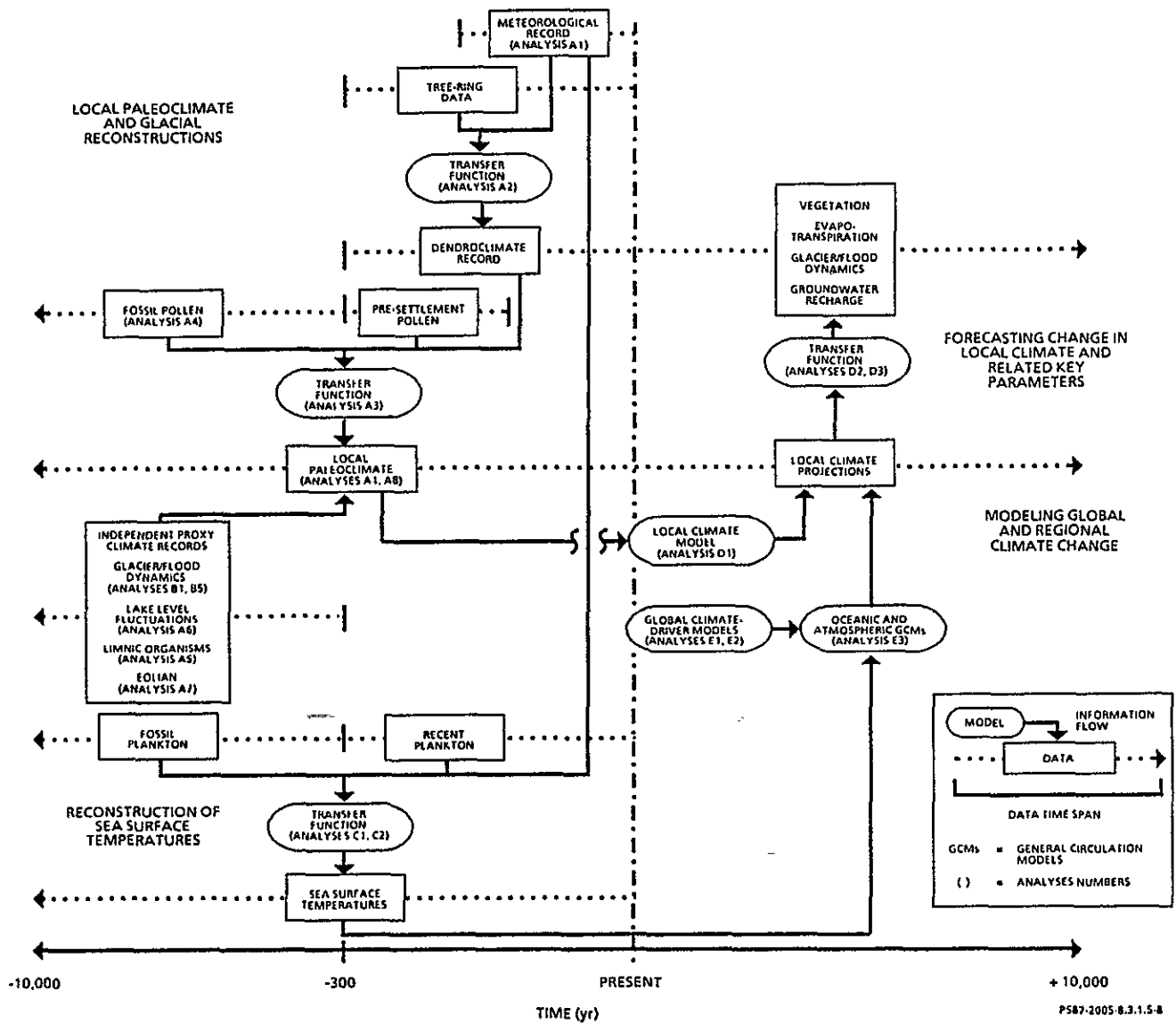


Figure 8.3.1.5-3. Analyses included in the specific program of investigation of climate change at the Hanford Site. The figure summarizes the information flow and interdependencies of the various analyses.

The eight analyses included in this study component are as follows:

- A1--Synthesis of existing information.
- A2--Defining standard climate.
- A3--Calculation of pollen/climate transfer functions.
- A4--Collecting fossil pollen data.
- A5--Collecting lacustrine biotic data.
- A6--Collecting and interpreting lake level fluctuation indicators.
- A7--Determining paleo windflow patterns.
- A8--Reconstructing paleoclimates at specific times.

All eight of these analyses must be completed by the end of FY 1993 to test the models designed to forecast future climates. Boundary conditions required for that test will be derived from the regional paleoclimate characterization studies (Analyses B1 and C1). The local climate model for the Pacific Northwest (Analysis D1) will create a description of the paleoclimate under a set of boundary conditions. This process will create a climate that is reconstructed from two independent sources of evidence, the pollen-stratigraphic techniques (Analysis A8) and modeling. An important test of the capabilities of the climate model will thus be available.

In addition to the applications of the paleoclimate characterization for testing the forecast model, reconstructions of paleoclimate will also provide a set of bounding scenarios to serve as input to a regional model of long-term groundwater flow of the Columbia Plateau (see Chapter 3 and Section 8.3.1.3). Modeling of groundwater flow will begin in FY 1992, and paleoclimate bounding scenarios must be available.

All analyses in this study component will focus on the Columbia Plateau and surrounding mountains. Core-top samples of pollen will be derived from a larger area than the palynologic reconstructions. This will ensure that the range of species and climates included in the sample represent those to be encountered in the smaller area over a longer timespan. To supplement the palynological data, a literature-based synthesis of paleoclimates for the entire Pacific Northwest will be completed early. This will identify major gaps in knowledge and set the reconstructions in a regional context.

As a well established paleoenvironmental discipline, palynology possesses a standardized, widely accepted suite of analytical methods (Birks, 1981; Faegri and Iversen, 1975). Assumptions underlying the reconstruction of vegetation and climate from fossil pollen have received considerable study (Davis, 1967; Davis et al., 1973; Birks, 1981; Overpeck et al., 1985; Prentice, 1985). Comparisons have been made among the different approaches to constructing statistical relationships used in pollen/climate transfer functions (Webb and Clark, 1977; Kay and Andrews, 1983).

Strategies for identifying and minimizing the sources of the uncertainty in paleoclimatic estimates have been defined (Bartlein et al., 1984; Bartlein and Webb, 1985; Howe and Webb, 1983). First attempts to apply these strategies to the Pacific Northwest have been made (Heusser et al., 1980; Mathewes and Heusser, 1981). The BWIP paleoclimatic reconstructions will

benefit from recent studies showing how to determine the applicability of alternative quantitative approaches (Overpeck et al., 1985; Bartlein and Webb, 1985).

Of the eight analyses described in this section (Analyses A1 through A8), the first (Analysis A1) is based totally on literature and requires no analytical procedures (Table 8.3.1.5-6). Analysis A2 relies primarily on the procedures of dendroclimatology (Table 8.3.1.5-6). This field is well established, but it will require some development of Autoregressive Moving Average (ARMA) modeling, simulation modeling and related analytical techniques to obtain time stability and to evaluate procedural differences (Fritts, 1985). Similarly, the procedures of development of transfer functions (Analysis A3) rely heavily on established statistical procedures (Bartlein et al., 1984).

Analyses A4 through A7 will collect the field data of paleoclimatic parameters required for the final paleoclimatic reconstructions. Pollen data are to be collected from cores of lake sediments in Analysis A4. Other lacustrine biotic data (primarily diatom abundances) will be recorded for the same cores in Analysis A5. Nonbiotic indicators of lake-level fluctuations and hydrologic and climatic data required for geohydrologic interpretations of lake level fluctuations in the geologic setting will be collected and interpreted in Analysis A6. Eolian deposits will be examined in Analysis A7 to extract information about paleo windflow directions and speeds.

The paleoclimatic reconstructions (Analysis A8) require the knowledge of many experts in paleoclimatology. Exact procedures are not defined; these will be determined by professional judgment. The quality of that judgment will be studied following the reconstruction by using quantitative measures of reproducibility. Procedures that are known to be needed in the paleoclimatic studies are listed in Table 8.3.1.5-5.

8.3.1.5.3.3.1.1 Analysis A1--Synthesis of existing information.

Published information provides a wealth of concepts about climatic changes for many areas immediately adjacent to the Pasco Basin. The results of this work are, in many cases, directly relevant to the characterization of paleoclimate at the Hanford Site. To ensure that this information is available in the climatological studies and to assess the degree of certainty (or uncertainty) in the interpretations of the existing information, a synthesis of paleoenvironmental literature spanning all relevant disciplines will be executed in Analysis A1. Where information gaps exist in needed information, these will be identified and additional plans to resolve those information needs will be defined. Instrumental climatic records will be assembled from existing sources, and corrections for known biases will be performed (Karl et al., 1986).

8.3.1.5.3.3.1.2 Analysis A2--Defining standard climate.

In order to accurately model the present groundwater system and to reconstruct the regional paleoclimates, a baseline or standard climate must be defined. Statistical parameters of recorded weather data and reconstructed variations over the last 500 yr will be used to establish this "standard climate." This

Table 8.3.1.5-6. Local paleoclimate analyses procedures

Analysis number	Analysis	Procedure
A1	Synthesis of existing information	Computer-based reference system maintenance, selection of relevant literature, selection of existing climate data, correction of climatic data, summarizing literature, review of summaries
A2	Defining standard climate	Data transfer, tree-ring station selection, tree-ring site selection, tree selection, tree coring, field management of tree-ring cores, transportation of tree-ring cores, laboratory storage of tree-ring cores, measuring tree-ring cores, recording of tree-ring data, cross-dating and checking tree-ring cores, construction of transfer functions between climate and tree-ring data, application of transfer functions to entire tree-ring record
A3	Calculation of pollen/climate transfer functions	Construction of pollen/climate transfer functions, testing of pollen/climate transfer functions, application of pollen/climate transfer functions to long-core pollen data, peer review
A4	Collecting fossil pollen data	Pollen analysis site selection, site reconnaissance, selection of candidate sites, sediment coring with Livingston corer, sediment coring with short-core samplers, sediment core management in field, core transportation, laboratory storage of cores, core description, core sampling, equipment calibration, data recording, transfer of core samples
A5	Collecting lacustrine biotic data	Data transfer, sediment core/sample transfer, radiocarbon dating, tephrochronology, magnetostratigraphy, varve counting, fossil identification, data synthesis, peer review
A6	Collecting and interpreting lake level fluctuation	Lake-site selection, core-location selection, obtaining lake cores, field management of lake cores obtained, laboratory storage of lake cores, lake-core sampling, transfer of lake-core samples, isotope analysis, macrofossil identification, radiocarbon dating, tephrochronologic dating, data recording, lake-level reconstruction Transfer of lake-core samples, $^{16}\text{O}/^{18}\text{O}$ analysis, hydrogen/deuterium ratio analysis, geochemical analysis, indicator mineralogical analysis, sedimentological analysis, data synthesis
A7	Determining paleo windflow patterns	Dune, tephra, and loess deposit site selection; core-location selection; obtaining deposit-cores; field management of cores; core sampling; transfer of core samples; exposure-location selection; exposure sampling; dune identification; dune mapping; dune sampling; mineral composition identification; radiocarbon dating; tephrochronologic dating; data recording; source area identification
A8	Reconstructing paleoclimates at specific times	Data transfer, conversion of data to groundwater model format, development of paleoclimate reconstructions, reconstruction testing and analysis, transfer functions testing and analysis, data synthesis

PST88-2014-8.3.1.5-4

standard climate will provide the input for modeling the present groundwater system and will serve as a reference point for the transfer functions that will be developed during Analysis A3. The standard climate will be defined based on dendroclimatic data for the period 100 to 500 yr ago and weather station data for the period from 100 yr ago to the present.

Dendroclimatic analysis will be needed to aid in the construction of transfer functions relating the abundance of pollen of various species to the actual climate that existed at the time the pollen was deposited. It is necessary to avoid pollen spectra of the past 100 yr when constructing such transfer functions, because species composition has changed so drastically with land alteration and the introduction of cultivated and nonnative "weed" species. The modern pollen rain is no longer the product of vegetation in equilibrium with climate. Therefore, transfer functions must be constructed that relate pollen and climate at some earlier time (before 1880). Using dendroclimatology, the climate of the region over the past 100 to 500 yr will be reconstructed. Once the paleoclimate has been reconstructed by dendroclimatology, standard methods of pollen analysis (Arigo et al., 1984) will be used to statistically relate the paleoclimate with correlative paleopollen spectra. Careful dating methods must be applied to allow the correlation of spatial and temporal variations. Such correlation methods will be a difficult task.

A second application of the standard climate reconstructed with dendroclimatology will be to define the recent climate of the area. This will supplement the instrumental record, which, in some cases, is less than 30 yr. There is clear evidence that variations in climate over the past 500 yr have exceeded variations recorded in the past 30 yr (Williams and Wigley, 1983; Heusser, 1957; Heikkinen, 1984; Blasing and Fritts, 1976). Therefore, the instrumental record alone is not representative of recent conditions of recharge to the regional groundwater flow system (see, for example, Diaz, 1986). At present, it is unknown what resolution in estimates of recharge can be achieved with this method. Determination of the resolution that can be achieved, and the resolution that is required will be an early part of the BWIP studies.

Although useful tree ring data cannot be collected from within the Pasco Basin proper, there are sufficient records available in higher elevation areas surrounding the Pasco Basin. Such records have been applied to estimation of climate in the Pasco Basin (Cropper and Fritts, 1986). Procedures for such work, as well as means of extrapolation, must be carefully considered and tested.

8.3.1.5.3.3.1.3 Analysis A3--Calculation of pollen/climate transfer functions. Availability of transfer functions will allow the use of pollen data (Analysis A4) to reconstruct the paleoclimates of the Pasco Basin (Analysis A8). These reconstructed paleoclimates will form the basis for statements about the range of changes in climate that are possible over the

next 100,000 yr. Since the regional climate will be characterized at 3,000-yr intervals (see Analysis A8), an estimate of the net rate of change of climate over these periods can be made. This may not represent the maximum or minimum rate of change during that period. Both of these items are requested by Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2).

8.3.1.5.3.3.1.4 Analysis A4--Collecting fossil pollen data. An analysis of the Quaternary paleoclimatology of the candidate area and site is needed, and it must be supported with geologic, biological, and ecological evidence in accordance with the recommendations of Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1).

Palynology is the only means of paleoclimatic reconstruction that has been widely applied in the Pacific Northwest (Heusser, 1983; Baker, 1983). There is a reasonably large number of sites in the Columbia Plateau and adjacent regions where pollen data have already been collected (Fig. 8.3.1.5-4) (Baker, 1983; Mehringer, 1985). Thus, the primary method of satisfying this information need is by collection of fossil pollen and reconstruction of late Quaternary paleoclimates (see Analysis A8). Emphasis will be placed on obtaining records that extend back through the last glaciation. Where practical, paleoclimatic records that extend back through the previous interglacial (oxygen isotope stage 5e) will be obtained. There are a limited number of sites where such long records can be expected to be available. This places severe constraints upon the details of paleoclimate reconstructions that can be obtained.

Data made available from this analysis will form the primary input to the analysis (see Analysis A8) that will create the paleoclimate reconstructions. The basis of this reconstruction will be the application of the pollen transfer functions produced from Analysis A3.

Independent of the reconstructions that are to be produced at 3,000-yr intervals of time, other reconstructions are possible that may offer some advantages. In particular, the widespread occurrence of volcanic ash layers in the Pacific Northwest (see Section 5.2) provides datable time horizons that can be more readily identified in most sedimentologic records. The BWIP will consider the use of certain of these horizons for paleoclimatic reconstructions. One disadvantage to using these other time periods is that they are not associated with global reconstructions, as are the 3,000-yr intervals. This eliminates the opportunity to understand the local climate, which is reconstructed within the broader hemispheric and global system. Since a major purpose of the paleoclimatic reconstructions is to provide an understanding of the manner in which future climates may evolve, it is more desirable to examine local reconstructions within the broader system that controls those changes.

8.3.1.5.3.3.1.5 Analysis A5--Collecting lacustrine biotic data. Guidelines provided by Regulatory Guide 4.17 (NRC, 1985, Section 5.1.1) suggest that the analysis of paleoclimates include an assessment of the applicability and validity of the reconstructions. Such information will be provided through independent, supporting lacustrine biotic data. Fossil

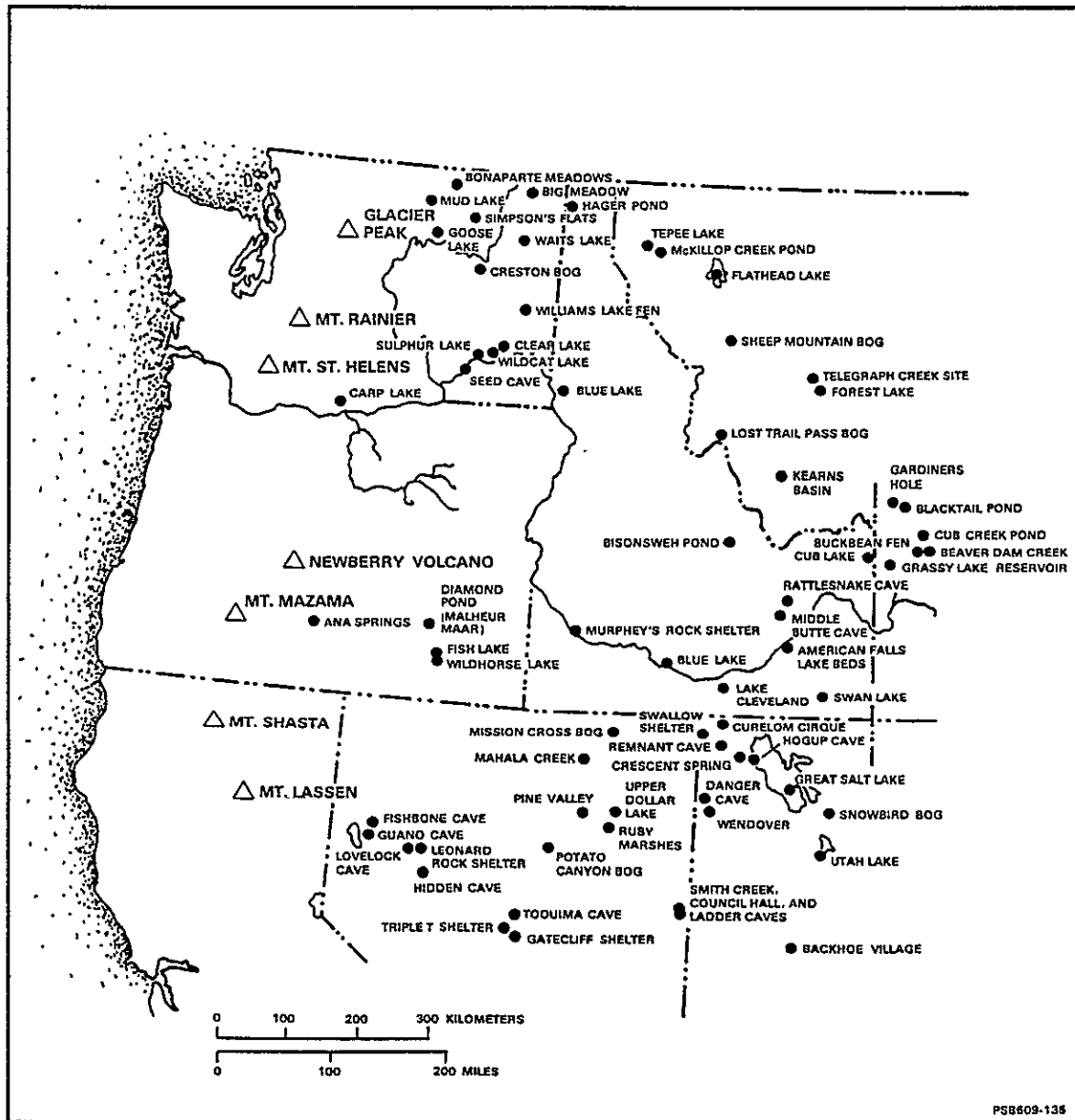


Figure 8.3.1.5-4. Locations of some of the sites in the northwestern United States at which pollen samples have been collected (from Mehringer, 1985).

diatoms ostracods and algae and plant macrofossils selected from the same locations as the fossil pollen data and subject to an analogous paleoclimatic interpretation procedure, will be considered for use to assess the consistency of the pollen studies (Analysis A4).

One potential problem with the use of fossil diatoms (and other proxy indicators) is that the record prior to the Holocene is sparse and may have been removed by Scablands erosion in lakes below 335 m (1,100 ft). It is not certain that sufficient species are available to bracket the range of paleoclimatic variability. Nor is it known whether such species are sensitive to the magnitude of climatic change that has occurred in the Columbia Basin. Because of these potential limitations, these lacustrine biotic records cannot be relied upon as the primary vehicles for paleoclimatic reconstructions.

These lacustrine biotic data will be used principally to provide estimates of the magnitude of lake-level fluctuations throughout the period represented by the sediment cores. These reconstructions of lake level changes can be used to make first-order estimates of fluctuations in groundwater in the unconfined aquifers of the Columbia Plateau. These data will be combined with other data (such as geochemical indicators) collected in conjunction with Analysis A7 and will be interpreted in that analysis.

Paleoclimatic reconstructions based on the lacustrine biotic data chosen, given the sediments under analysis, will supplement and provide tests of pollen-based paleoclimatic reconstructions (Analysis A8). Such data will also be used to refine the pollen-based reconstructions and may provide the ability to link the long-term (thousands of years), proxy climatic record with the short-term (tens of years) instrumental record of historic climatic variation. Such a link would derive from the higher resolution of record that could be obtained from the lacustrine biotic data. This will provide another important measure of the validity of the reconstructions.

8.3.1.5.3.3.1.6 Analysis A6--Collecting and interpreting lake level fluctuation indicators. Of great concern in considerations of the long-term geologic stability of the Hanford Site is the possibility of radionuclide transport by groundwater. The geologic evidence capable of reflecting on the possible changes in the groundwater system is limited and difficult to obtain. An important source of such information is the fluctuations in the levels of lakes in the surrounding region. Although the variations cannot be directly measured, they can be interpreted from the geochemical and sedimentologic evidence of lake-level fluctuations. Examples of such evidence include: drowned and buried meadow soils and trees, strand lines, tufa deposits, and core chemistry (Mehring, 1985). This analysis will be conducted in conjunction with the collection of cores representing the past 500 yr of sediment record (Analysis A4) so that the records of water levels, lake volumes, and surface areas can be correlated with microfossil types and abundance, grain size and source area, and the mode of deposition (eolian or slopewash). There will be an examination of the cores for distorted laminae and their use as indicators of past tectonic activity (Sims, 1975). This could include x-rays of many lake cores. Most of these lakes are directly connected to the groundwater system, so fluctuations of the one will be

reflected in the other. Methods have been developed to reconstruct, at least partially, the history of such lake fluctuations (Winter and Wright, 1977; Gillespie et al., 1983). Because of erosion attributed to Missoula floods, it is unlikely to find many lakes with sediments older than Holocene age.

A major application of the results of the paleoclimate characterization is to provide a measure of the stability of the groundwater system. One important measure of that stability is the extent to which the groundwater table has fluctuated during the Quaternary.

Variables used to reconstruct such fluctuations from geologic information include the physical and chemical properties of lake sediments (Birks and Birks, 1980). This analysis will provide the nonbiotic evidence of lake level fluctuations in the Columbia Basin. The results of this analysis will be used to address questions concerning the hydrologic system in successive climatic regimes and to identify the locations of potential aquifer recharge areas as requested by Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1).

Using modern data on lake-level fluctuations, the geohydrologic significance of lake-level fluctuations in the Pasco Basin will be reconstructed. These reconstructions, combined with data from Analysis A6, will provide the basis for estimating the corresponding variations in groundwater conditions during the late Quaternary. Finally, an attempt will be made to correlate the fluctuations with the broader record of climatic change.

Regulatory Guide 4.17 suggests an assessment of the "relationships between air temperature and regional precipitation, in relationship to the water balance of the area" (NRC, 1985, Section 5.2.1). The results of this analysis will provide the most direct and reliable evaluation of those relationships. The information will be used as a guide to specify those climatic changes that are potentially destabilizing.

8.3.1.5.3.3.1.7 Analysis A7--Determining paleo windflow patterns. In Regulatory Guide 4.17 (NRC, 1985, Section 5.1.1), the NRC requests that the DOE provide information about past and expected future windflow regimes and the potential changes and rates of change that can occur in these. Windflow information is relevant to the characterization of the climatic stability of the Hanford Site since it allows first-order estimates of the changing influence of the global climatic regime at the site. The orientation of major windflow patterns provides a basis for estimating the precipitation at the site. Windflow information, especially the speed of winds, is important in the computation of evaporation and evapotranspiration in the area. This is critical for complete estimates of the infiltration and recharge to the groundwater system. Observational data of modern windfields have been reported by Wendland and Bryson (1981).

Paleo windflow directions and magnitudes can be estimated through the examination of eolian deposits. Examples of useful deposits in the Pacific Northwest include sand dunes, loess deposits, and tephra. Dispersal patterns of indicator mineralogies has also been used for more general studies. These methods are discussed in greater detail in Chapters 1 and 5 and the references cited there.

Studies of dune fields suffer from difficulties of establishing chronologies for episodic eolian activity (Kutzbach and Wright, 1985; Mehringer and Wigand, 1986; Ahlbrandt, 1983). Because of this, it will be prudent to establish and evaluate the chronologies of available dune fields before continuing the analysis. That work would continue only if the chronologic controls warrant it.

The paleo windflow information derived in Analysis A7 will be used for paleoclimatic reconstructions (Analysis A8). The same information will be made available to the pollen-based paleoclimatic reconstructions to improve estimations of pollen dispersal routes. Paleo windflow estimates will be used in Analysis D1 to calibrate and test the model of local climatic variability. Finally, the same information will be used in Analysis E3 to compare to the regional windflow patterns reconstructed by the general circulation model.

8.3.1.5.3.3.1.8 Analysis A8--Reconstructing paleoclimates at specific times. In Issue 1.9, the BWIP has identified the need to evaluate the magnitude of climatic change during the Quaternary. This information will allow a decision on qualifying condition 10 CFR 960.4-2-4 (DOE, 1987). Knowledge of the magnitude of climatic change during the Quaternary will also allow a decision on favorable condition 10 CFR 960.4-2-4(b)(2). Thus, the DOE has clearly indicated the need to understand the range of climatic change that has occurred during the Quaternary. Analysis A8 will provide a synthesis of information derived in Analyses A1 through A7 in order to characterize the range of Quaternary paleoclimates.

The NRC guidelines explicitly state that an assessment of paleoclimatic conditions at the candidate site should be included as a portion of the site characterization (NRC, 1985, Section 5.2.1). The site characterization should "Provide an analysis of the Quaternary paleoclimatology of the candidate area and the site...." This should include an analysis of "...precipitation regimes...." and "Relationships between air temperature and regional precipitation...." Such analyses are to be provided for "...the successive climatic regimes, in the context of determining the magnitude of the climatic changes and the rates at which the changes occurred."

To provide the information requested by the NRC for the licensing review, various data sets (Analyses A4 through A7) will be synthesized in a description of the paleoclimate of the area. These reconstructions are expected to be done for the time period extending from the present to 21,000 yr ago in 3,000-yr intervals. These "time slices" are chosen for the following reasons:

- They are representative of a broad range of climatic conditions (glacial through interglacial).

- The bulk of the available paleoclimatic data is known to represent this period.
- The same time slices are currently being reconstructed through the Cooperative Holocene Mapping Projects (COHMAP), a consortium of paleoclimatic researchers (Kerr, 1984).

Information will be provided in a format that can be integrated with computer models of the groundwater system. This will allow examination of the impacts of climatic change on the groundwater system.

The results of Analysis A8 will also satisfy the NRC guidelines that specify: "The validity and applicability of the information provided, with respect to the representation of conditions at and near the site, should be substantiated" (NRC, 1985, Section 5.2.1). The information provided by this analysis will provide a basis for estimating the uncertainties in reconstructions. These uncertainties (standard deviations) will allow meaningful statistical tests of skill of the local climatic model in fitting observed climate. Such tests are defined as part of the second study (see Analysis D1).

8.3.1.5.3.3.2 Study Component B: Quaternary history of glaciation in the Pacific Northwest

Paleoclimatic reconstructions for the Columbia Plateau partially depend on the knowledge of past glacial events. For example, climatic zonation and the magnitude of climatic gradients depend on the location of the glacier margin at a given time. Thus, the glacier reconstructions are a natural part of the paleoclimatic characterization. The current understanding of those events is summarized in Section 5.2.1.2.

Further examination of the disruption of drainage systems by the growing glaciers is required because understanding the disruption sequence requires knowledge of glacier history. Similarly, understanding the history and characteristics of major floods in the Pasco Basin (the Missoula floods and the Bonneville floods) also requires information about the glacial history, since nearly all of those floods were the direct result of the failure of glacial dams of lakes (Clarke et al., 1984).

The analyses of regional glaciation are also needed for the local climate model (Analysis D1). The configuration of the cordilleran Ice Sheet must be specified to run the local climate model. As a result of these analyses, that configuration will be estimated at 3,000-yr intervals since the beginning of the last glacial maximum (21,000 yr ago).

The following five analyses are included in this study component:

- B1--Specifying glacial configurations.
- B2--Defining dynamics of glacier movements.
- B3--Documenting river disruption by glaciers.
- B4--Specifying behavior of major glacial floods.
- B5--Investigating groundwater disruption by floods.

Stratigraphic methods will be used to supplement the existing information about the glaciation of the area where gaps exist (Analysis B1). Similar field mapping procedures will be used to characterize the dynamics of the ice sheet (Analysis B2), effects of that ice on the major rivers of the area (Analysis B3), and behavior of the large floods produced by failure of ice dams (Analysis B4). The possible disruption of the groundwater by flood water incursion (Analysis B5) will be studied using hydrogeologic techniques. These items are grouped as a single study component because they relate to glaciation and glacially derived phenomena. Methods of analysis are similar in all except Analysis B5, which is included because it requires the results of the other analyses for conclusions.

A natural progression of increasing understanding about the Hanford Site will be achieved as the analyses are completed in their order of presentation. The effects of floods on the groundwater system (Analysis B5) depends on the flood dynamics (Analysis B4). Flood dynamics depend on the mode of disruption of the drainage systems by glaciers (Analysis B3). The timing and magnitude of these disruptions depend on ice sheet dynamics (Analysis B2).

Characterization of glacier dynamics requires a representation of the configuration of the glacier at various times in its growth and decay (Analysis B1).

Methodologies of Pleistocene stratigraphic investigations have been thoroughly developed over the past 100 yr (Bowen, 1978). These methods will be the principal ones applied in all of the analyses of this study component. Field observations will be documented in accordance with accepted field mapping procedures (Compton, 1962). Current analytical procedures will be adequate to complete this study component. Those analytical procedures known to be required for the glacial geological study component are listed in Table 8.3.1.5-7.

8.3.1.5.3.3.2.1 Analysis B1--Specifying glacial configurations. Glaciers influence sea level and atmospheric circulation; therefore, they are important in reconstructing paleoclimate. By their sheer size, they impede and divert the normal airflow and extract moisture by orographic uplift. When extensive, glaciers modify the drainage system of the region. This analysis will produce a set of maps to show the magnitude and extent of glaciation in the Pasco Basin at various times in the late Quaternary to permit estimates of the effects of such glaciation on the local climatic system.

The information provided by Analysis B1 will be used to respond to Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1), which solicits information relevant to the "size (aerial extent and thickness) of any glaciers" and on "accumulation and ablation rates." The requested documentation of "The impacts of any glaciers on precipitation regimes and windflow patterns...." is also to be supplied.

Table 8.3.1.5-7. Glacial geological analyses procedures

Analysis	Analysis	Procedure
B1	Specifying glacial configurations	Literature search and reference system maintenance; field identification, trenching, and mapping of glacial deposits; compilation and interpretation of well logs of wells drilled in flood deposits; radiocarbon dating; tephrochronologic dating; mapping and interpretation of aerial photographs and satellite imagery; data synthesis
B2	Defining dynamics of glacier movements	Literature search and reference system maintenance, field identification and mapping glacial deposits/features, mapping and interpretation of aerial photographs and satellite imagery, radiocarbon dating, tephrochronologic dating, data synthesis
B3	Documenting river disruption by glaciers	Literature search and reference system maintenance, field identification and mapping of deposits/features, radiocarbon dating, tephrochronologic dating, mapping and interpretation of aerial photographs and satellite imagery, data synthesis
B4	Specifying behavior of major glacial floods	Literature search and reference system maintenance, field identification and mapping of flood deposits/features, radiocarbon dating, tephrochronologic dating, mapping and interpretation of aerial photographs and satellite imagery, compilation and interpretation of well logs of wells drilling in flood deposits, data synthesis
B5	Investigating ground-water disruption by floods	Stable isotope analysis, geochemical analysis of groundwater samples

PST88-2014-8.3.1.5-5

8.3.1.5.3.3.2.2 Analysis B2--Defining dynamics of glacier movements. Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1) requests an analysis of the "...cryospheric aspects of successive climatic regimes, in the context of determining the magnitude of the climatic changes and the rates at which the changes occurred." As a portion of the forecast of future climatic fluctuations, the site is responsible for indicating the "future fluctuations in...[the] cryosphere due to climatic change."

Assessing past glaciations and forecasting future ones require a comprehensive understanding of glacier dynamics. In Analysis D2, forecasts will be prepared using a computer model of ice sheet dynamics. The model will be calibrated and tested using the geologic record synthesized in Analysis B2.

8.3.1.5.3.3.2.3 Analysis B3--Documenting river disruption by glaciers. During major glacial events, the Cordilleran Ice Sheet extends downward, far from its centers of growth in the higher mountains of British Columbia. At these times, the ice sheet disrupts smaller drainage networks and blocks larger rivers (see Section 5.2). Disruptions could include impounding bodies of water, changes in discharge, and aggradation or degradation of sediments in river channels and in alluvial fans at the mouths of rivers. These changes may accompany each major glaciation the area experiences. This analysis will document such changes and estimate the influences they would exert on the hydrologic system, especially the Columbia River and its major tributaries. An important tributary, the Snake River, was the scene of very large floods derived from glacial Lake Bonneville. Its discharge was also modified by glaciation in its headwaters. The effects of such disruptions upon the Pasco Basin will be considered, and plans for use of this information are provided in Section 8.3.1.3.

The ultimate fate of a great deal of the sediment that was transported by these major floods was deposition in the Pacific Ocean. One focus of deposition was the Astoria deep sea fan located at the mouth of the Columbia River. Future floods could also lead to sedimentation at this same area. It would be useful to study the characteristics of flood sedimentation in the Astoria fan for several reasons. Such sediments may allow the most precise estimates of the probability, magnitude, number, and timing of past floods. The record there might extend beyond the floods of the last glaciation. This information would provide a more complete basis for estimation of the potential for disruption of the repository than would land records alone. Analysis of these sediments could also provide the basis for estimation of the fate of nuclear materials that might enter the Columbia River. For these reasons, the BWIP is considering a separate examination of sediments in the Astoria fan. This would probably require coring from a ship. A group of experts will be convened early in the site characterization program to determine the advisability of such an analysis. If such an analysis is deemed necessary, future updates to the SCP will reflect this decision.

Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1) requires an analysis of the "hydrospheric" aspects of the various "successive climatic regimes." Analysis B3 will provide one aspect of that information. It will also serve to define the model of future glaciations that will be needed to forecast such disruptions.

8.3.1.5.3.3.2.4 Analysis B4--Specifying behavior of major glacial floods. The Pasco Basin was subject to floods of vast proportions during the Quaternary. The most recent occurred about 13,000 yr ago (Mullineaux et al., 1978; see Section 5.2). Floods like these could disrupt the site in the future, and their possibility must be considered. Forecasting the behavior of future floods requires documentation of the nature and effects of previous floods. This documentation will guide the construction and provide the data to test the model of future floods (Analysis D3).

8.3.1.5.3.3.2.5 Analysis B5--Investigating groundwater disruption by floods. Major floods within the Pasco Basin may be of sufficient depth and duration to produce pressurized recharge of the groundwater system. Vast volumes of water would be involved. If a slight fraction of the flood water was introduced into the groundwater system, it might constitute a major fraction of the total groundwater volume. Such recharge seems possible because of the fractured nature of the basalt near the surface. This basalt could become exposed in the early stages of a flood because of the entrainment of the overlying unconsolidated sediments at the surface; therefore, the possibility that such recharge has occurred during previous floods must be investigated. This analysis will be integrated with research described in Section 8.3.1.3 concerning groundwater disruption by major floods.

Analysis B5 will provide a portion of the information that will be required for the analysis of "changes in locations of potential aquifer recharge areas" Such an analysis is required by Regulatory Guide 4.17 (NRC, 1985, Section 5.2.1). The information will be used in groundwater models of the site.

8.3.1.5.3.3 Study Component C: climatic history of the northeast Pacific Ocean.

Climatic variability in the Pasco Basin is influenced by variations in oceanographic conditions. Additional information about the variability of sea surface temperatures off the coast of Washington State over space and time is required (see Section 5.2.1.3). This study component includes the analyses needed to characterize that variability.

Atmospheric variations are estimated using atmospheric general circulation models for climatic forecasts. Results of glacial and oceanic reconstructions provide the boundary conditions necessary to run the models. The results of the analyses that use atmospheric general circulation models will be tested against the paleobiotic-based reconstructions for the region. Thus, the analyses of Section 8.3.1.5.2 form a single coherent and integrated characterization of paleoclimate.

The results from atmospheric general circulation model runs are required as input to the local climate model (Analysis D1). Another necessary boundary condition for the local climate model is the sea surface temperature pattern. Understanding the oceanic conditions is required for global and local climate forecasts. The climatic patterns will be characterized from deep-sea cores and the faunal record preserved in the ocean sediments.

Information derived from oceanographic studies must be integrated with local paleoclimatic reconstructions, and the consistency of the two must be tested. For this reason, both the ocean and land records must be reconstructed at the same time horizons. Those horizons will be recognized using common stratigraphic controls and mutually acceptable dating methodologies. Thus, the efforts of these two study groups must be integrated carefully.

The two analyses included in this study component are as follows:

- C1--Reconstructing Quaternary sea surface temperature histories.
- C2--Reconstructing sea surface temperature patterns at selected times.

Characterization of oceanographic patterns (Analysis C2) will use cores taken in the northeast Pacific Ocean bordering the coasts of Oregon, Washington, and southern British Columbia. Abundance of key planktonic taxa will be measured to allow estimates of paleo sea surface temperatures. Such an approach has been applied in the northeast Pacific Ocean by Moore et al. (1980) and Moore (1973). Additional work has been done in the north-central Pacific Ocean by Sachs (1973).

Analysis C1 will examine the variability of sea surface temperature at one place over a long timespan. In this way, an estimate of the long-term variability of the northeast Pacific Ocean can be obtained. This will form

the basis of estimates of the probability of various climatic states. Such an estimate is needed since the BWIP must consider any (unanticipated) climatic states with probability greater than 0.00001 over the next 10,000 yr (see glossary). The correlation between long-term variability of the northeast Pacific Ocean and global controls on climatic change (e.g., solar insolation) will be measured to determine if predictions of the climatic state of the area are feasible and the amount of error inherent in such predictions.

Paleo-oceanographic techniques have been developed to a high level of sophistication over the past three decades. The methods generally involve analysis of fossil fauna preserved in the oceanic sediments and retrieved using piston coring procedures. Analysis of the faunal assemblages uses quantitative statistical methods. Interpretations are based on the known controls on the oceanographic characteristics of an area and the regional setting. These concepts have recently been reviewed in detail by Ruddiman (1985). Technical procedures that will be defined for Analyses C1 and C2 are listed in Table 8.3.1.5-8.

8.3.1.5.3.3.3.1 Analysis C1--Reconstructing Quaternary sea surface temperature histories. A major factor controlling global climate change is the quasicyclic variation in the orbital parameters of the earth. The importance and phase relations in this change vary at least latitudinally. Since it has not been explicitly studied, it is not clear to what extent the changes in the Pacific Northwest correlate with this global influence. Analysis C1 will determine the history of climatic fluctuations in the oceanic area adjacent to the Washington coast and will examine the relations between the oceanic changes and the various proposed controls on long-term climatic changes. One of the sediment cores used in Analysis C2 will also be used for this analysis.

Table 8.3.1.5-8. Paleo-oceanographic analysis procedures

Procedure	Analysis	
	C1	C2
Selection of oceanic sediment cores	X	X
Transfer and storage of sediment cores	X	X
Sampling of oceanic sediment cores	X	X
Analysis of oceanic sediment core data		X
Isotope analysis	X	
Radiocarbon dating	X	
Tephrochronologic dating	X	
Fossil identification	X	
Construction of transfer functions	X	X
Spectral analysis of core data	X	
Peer review	X	X

The results of this analysis will address the NRC request (NRC, 1985, Section 5.2.1) for "...an analysis of the...hydrospheric...aspects of successive climatic regimes, in the context of determining the magnitude of the climatic changes and the rates at which the changes occurred." The information will provide a measure of the predictability of global climate change using models described in the global climate change study component (Analysis E1). This will provide the most direct tool available to estimate the probability of different climatic states in the next 100,000 yr as required to satisfy 10 CFR 960.4-2-4(b)(1) (DOE, 1987).

Paleo sea surface temperature estimates will be made from fossil plankton assemblages using available core. These sea surface temperature records will be subject to a spectral analysis to determine the strength of the Milankovitch signal and a cross spectral analysis to determine the coherence with that signal.

8.3.1.5.3.3.2 Analysis C2--Reconstructing sea surface temperature patterns at selected times. Considerable evidence is available that demonstrates the importance of sea surface temperatures in the Pacific Ocean to climate in the western U.S. (Rogers, 1976; Barnett, 1981; Walsh and Richman, 1981; Sheaffer and Reiter, 1985). This is discussed in more detail in Section 5.2. A factor influencing the local climate of the Pasco Basin, especially the precipitation regime, is the amount of precipitable water available. This depends, in part, on the rate of evaporation from the ocean surface, which is a function of sea surface temperatures. To understand the local climate, and especially how the climate may have changed during the Quaternary, the record of the sea surface temperatures of the northeast Pacific Ocean must be known. Knowledge of the link between the two will be a fundamental part of the information required to construct and test predictive models of local climate (Analysis D1). Sea surface temperature spatial patterns will be estimated in the northeast Pacific Ocean at specific time periods during the late Quaternary corresponding to the same periods studied for continental paleoclimate reconstructions (Analyses A1 through A8). The oceanographic information will form a boundary condition for the local climate model. The results of the model will be tested against the actual paleoclimatic record summarized in Analysis A8.

Information required for this analysis will be taken from cores of ocean sediments in the northeast Pacific Ocean. It is believed that existing cores can provide the needed data. Locations of some of the existing cores that have been used for paleoclimatic reconstructions have been shown in Section 5.2.

8.3.1.5.3.4 Application of results of investigation

Results from the analyses previously described will indicate the range of climates that the geohydrologic system has experienced. Scenarios defining the different distributions and amounts of recharge during the Quaternary will be provided to the groundwater models. Modeling with these parameters will reveal whether radionuclide releases at the repository are within acceptable limits under each of these configurations. Paleoclimate analyses will also

provide input to tectonic and geomorphic models (see Section 8.3.1.2). Another application will be to the ability of the climatic models (Analysis D1) to reproduce the climates documented for the Quaternary. This will be a critical validation tool to test (Silling, 1983) the models before they are used for forecasting future climates.

These applications will be supported by the final analysis of the local paleoclimatic study component (Analysis A8). That analysis is the end product of all of the analyses listed in that study component. Reconstruction of the climates (Analysis A8) will be based on the data from Analyses A4 through A7. These data will be interpreted with the aid of transfer functions (Analysis A3). The transfer functions require the definition of a standard climate (Analysis A2). The standard climate will also form a scenario for groundwater models of the present hydrologic system. All of the work will proceed within the context of the existing literature and will be guided by the known information (Analysis A1).

Each of the analyses for reconstruction of glacial histories (Analyses B1 through B5) will support subsequent study components in the study. In addition, each analysis will result in information that supports other activities in the climatology program.

- Analysis B1 will provide information needed to support the climatic modeling with the local climate (Analysis D1) and global atmospheric models (Analysis E3).
- Analysis B2 will provide information needed to test the model of glacial dynamics (Analysis D2) and forms a portion of the modeling system for future climatic forecasts.
- Analyses B3 and B4 will provide data needed to test and calibrate the model of flood dynamics (Analysis D3), which will be used to forecast such events in the future.
- Analysis B5 will provide input to the hydrologic modeling to evaluate the effects of major floods on the groundwater system.

Analyses that are part of the paleo-oceanographic study component will result in an understanding of the climatic history of the northeast Pacific Ocean that is sufficient to decipher the mechanisms of climatic change at the Hanford Site. Results will be input to the local climatic forecast model (see Section 8.3.1.5.4.3.1) and will set the boundary conditions. Predictions made with the local climatic model using the oceanographic reconstructions will be compared to the actual reconstructed climate at the Hanford Site. This will provide a validation test of the local climatic model before it is employed for forecasts of the future climate.

8.3.1.5.3.5 Schedules and milestones for investigation

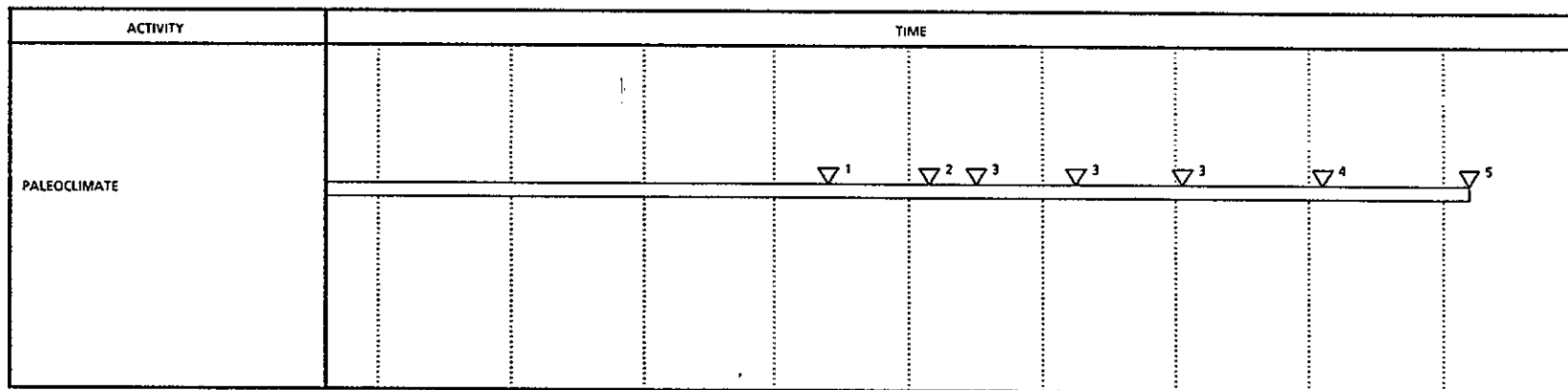
The following eight major reports will be produced from the local paleoclimates study components:

1. Summary of the available literature and a synthesis of the resulting paleoclimatic reconstructions (Analysis A1).
2. Definition of climatic variations over the past 500 yr and average climatic conditions during the same period (Analysis A2).
3. Transfer functions to be applied to the paleoclimatic indicator data (Analysis A3).
4. Pollen spectra retrieved and their analyses (Analysis A4).
5. Diatom analyses performed (Analysis A5).
6. Lake level fluctuation information retrieved and interpreted (Analysis A6).
7. Reconstruction of paleo wind patterns using eolian deposits (Analysis A7).
8. Summary statement of the paleoclimatic reconstructions themselves (Analysis A8).

The first three analyses (B1 through B3) of the glaciologic study component will result in a sequence of maps that illustrates the configurations of the glacier margins, dynamic paths followed by the ice, and resulting drainage system in effect at each of the time horizons chosen for analysis. The dynamic behavior of a typical Missoula flood (Analysis B4) will be described by a set of maps illustrating the flow paths, flow velocities and discharges, and water surface elevations that would typify major stages in a single flood event. The last analysis (B5) will be summarized in a report that describes the depth and duration of flood waters, characteristics of the overburden, amount of fracturing of the basalts, and probable maximum and minimum recharge likely to occur in various stages of a typical Missoula flood.

Generally, each of the paleoclimate analyses may proceed independently. However, there exist certain critical relationships that must be satisfied. A complete description of the schedule of work is provided in the following paragraphs.

Figure 8.3.1.5-5 shows the schedule and selected milestones for the past climatic change investigation. Early in the fourth year of the investigation the scope of most of the analyses will be reevaluated based on the results of sensitivity analyses of the groundwater system's response to climate change. Any changes in study scope will be reported in future updates to this chapter.



- ▽¹ STANDARD CLIMATE DEFINED.
- ▽² EVALUATION OF STUDY SCOPE BASED ON SENSITIVITY ANALYSIS.
- ▽³ INFORMATION ON CLIMATE CONSTRUCTION USING POLLEN, LAKES, GLACIERS, AND OCEAN SEDIMENTS PROVIDED TO THE FUTURE CLIMATIC CHANGE INVESTIGATION.
- ▽⁴ FINAL CLIMATE RECONSTRUCTION OF 3,000-YR INTERVALS PROVIDED TO THE FUTURE CLIMATIC CHANGE INVESTIGATION.
- ▽⁵ COMPLETE PAST CLIMATIC CHANGE INVESTIGATION.

PS48-2014-03.1.5-2

Figure 8.3.1.5-5. Schedule and selected milestones of the past climatic change investigation.

For most study components the first year will be spent investigating methods and implementing quality assurance procedures.

A synthesis of the existing paleoclimate information (Analysis A1) will comprise a significant portion of the entire data base available for the paleoclimate characterization effort. It will form an important guide for on-going analyses and the definition of gaps in the existing data base. Because the literature is extensive and growing, effort must begin early and continue throughout the research program. The work will start in the first year of study; however, it will be the most extensive in the second year of study and will continue at least through the end of the site characterization.

The primary and most useful form of results from these analyses will be the computerized reference system. A written report, summarizing current knowledge of paleoclimates, will be produced at the end of the second study year. Subsequent updates will be produced annually.

Analysis A2 will require 2 yr for completion. The calculations of pollen and climate transfer functions (Analysis A3) and reconstruction of paleoclimates (Analysis A8) cannot be completed until the results of Analysis A2 are available. Analysis A2 will be completed in the third year so the other two can be completed on time.

Appropriate personnel for Analysis A2 will be determined in the initial year of study. Also, the statistics of climatic stations and tests for consistency will be summarized by the end of the first year. Similarly, the statistics of the dendroclimatic reconstructions will be summarized and analyzed for consistency by the end of the second year. Synthesis of the dendroclimatic and climatic station data will be completed by the middle of the third year. Construction of a statistical model of the climate for the past 500 yr will be completed late in the third year. The results of the statistical climate model will be integrated with the hydrologic analyses in the following year.

Results of Analysis A3 must be complete before the climatic reconstructions of Analysis A9 can be completed. Therefore, the lakes to be sampled will be defined and a preliminary survey will be made by the middle of the second year of study. Early planning of the coordinated work and actual collection of lake cores and samples will be completed by the end of the following year. This will allow calculation of transfer functions and peer review of the results by the end of the fourth year of study.

Testing and refinement of the transfer functions will be completed by the middle of the fourth year. Such refinements will be limited to statistically acceptable methods within the limits of the data set chosen for model development. These final transfer functions will be applied to the pollen data from the long cores by the end of the fifth year. Applying the transfer functions to the longcores will allow the paleoclimate reconstructions

(Analysis A8) to be completed by the middle of the sixth year. Testing of the local climatic model (Analysis D1) using the results of these paleoclimatic studies will be completed by the end of the seventh year. Forecasts of future climate will be completed by the end of the following year.

Selection of the most appropriate lakes from which to obtain cores will begin in the first year. Cores from only three lakes will be analyzed (because expense and time required are prohibitive), which necessitates a careful survey and screening of potential coring sites. Peer review of the site selection procedure will precede actual coring operations. Coring of the lakes will begin in the second year and be completed in the following year. To ensure the timely completion of the pollen collection and analysis, separate study groups will operate independently at the different lakes. This will facilitate internal testing of the results to ensure that the highest data quality is achieved.

Early completion of Analysis A4 is required to allow sufficient time for pollen analysis and paleoclimate reconstructions. These will be completed by the middle of the fifth year to provide results with which to test the accuracy of the climatic forecast model (Analysis D1) before it is used for future climate forecasts.

Preliminary literature surveys for Analysis A5 will be conducted in the second year to determine which methods and classes of limnic organism will yield an acceptable supporting data set. If a suitable source and methods are identified, which will allow independent reconstructions for the Columbia Plateau, preliminary assay of the core-top samples used to construct the pollen and climate transfer functions (Analysis A3) will be completed during the next year. This assay will be used to confirm the selection of the most appropriate methods and data source to apply to the long cores. Splits of the long-core samples will be analyzed by the middle of the fourth year of study, and the interpreted paleoclimates will be summarized by the end of the following year.

Preliminary determination of the various nonbiotic climatic indicators appropriate for Analysis A6 will be completed in the second year. A report will be prepared stipulating which chemical and mineralogical analyses are most appropriate to reconstructing hydrologic conditions; then a peer review of the decisions will be conducted. Selection of lakes to be cored will also be done in the same year in conjunction with the planning of Analysis A4. Lake cores and samples will be collected during the third year. The chosen nonbiotic analyses will be completed about 2 yr later. Interpretation of results in collaboration with the work of Analysis A8 will be completed by the end of the sixth study year. The results of this analysis will be incorporated in the general paleobiotic reconstructions by the end of the following year. This will ensure that the results will be available for use in groundwater models by the end of the eighth year of study.

Analysis A7 will begin with a review of available information. Field work to collect windflow indicators from available eolian deposits in the

Pacific Northwest will occur in the third and fourth years. This work will be summarized in a form compatible with the general reconstructions and will be reviewed in the fifth study year.

Consistent and comprehensive paleoclimate reconstructions (Analysis A8) will be ensured by a working group of five to eight qualified researchers. Preliminary arrangements have already been made to collaborate with appropriate scientists that are conducting ongoing paleoclimatic studies. Members will be chosen in the second study year, and the first organizational meeting will be held then.

The purpose of early meetings in the third year will be to review sites chosen for data collection, review, and comment on the interpretation of existing data, establish uniform means of data transfer, and select approaches to the development of pollen-climate transfer functions.

As work progresses, meetings will concentrate on review of the results of new data collected and preliminary interpretations of those data. The working group will also define contingency plans for the paleoclimatic reconstructions, as needed. Actual synthesis of the interpretations to produce the climatic characterizations for each time period will be conducted in the fifth and sixth years.

Review and testing of the paleoclimatology characterization will be a regular and ongoing study component of the total study and will continue through the study. As milestones are reached, results of individual analyses (or significant portions of analyses) will be made available, and the advisory panel will assign peer review tasks to appropriate persons. This will draw on the expertise of the broadest possible range of active researchers. The review process will closely parallel that of a research journal.

The entire advisory panel will meet at 6-mo intervals to evaluate the overall progress in the research. At these meetings particular problems will be identified, and remedial actions will be defined. The meetings will also serve to ensure integration between this study component and other aspects of the study of climate change.

Field work planning for Analysis B1 is to be completed by the second year. The field work and a summary of the existing literature will be complete 2 yr later. This will allow a synthesis of new and existing information to be completed by the fifth study year. By the end of the following year, the resulting information will be incorporated into the modeling program.

Analysis B2 will begin with planning of field work and meetings of glacier dynamics experts to define methodology. Two years later, the literature review and field work will be completed. A synthesis of the available data and a summary of maps produced will be available for expert review in the fifth study year. The computer model (Analysis D2) will be calibrated and tested in the same year.

Analysis B3 will begin with organization of the field investigations, including the preliminary selection of the sites to be visited in the field. Work that will be completed during the following year will consist of compilation of the needed maps, photos, and images; literature review and synthesis; and field work. The available data will be interpreted, maps will be produced, and the results will be summarized and reviewed during the fourth year.

Analysis B4 consists of specifying behavior of major glacial floods. Sites to be examined and methodologies to be employed will be identified in the second year. A literature review and summary will be completed in the following year. Field work will also be completed then. By the middle of the sixth year, new observations will be integrated with existing information, and the results will be summarized as a set of maps. Review of these results will be completed by the end of the same year.

Initial consideration of the proper analytical tools to apply to Analysis B5 will be conducted in consultation with a group of experts on hydrologic studies in the second year. If methods can be defined and if there is a consensus that the problem should be more completely studied, actual analytical techniques will be determined during the following year.

Analysis C1 is scheduled to begin with a review of existing core data, selection of cores, and a decision on the need for additional cores. Cores chosen will be analyzed by the end of the fourth year. Statistical analysis of the results of these analyses and comparisons to the orbital record will be completed in the sixth year.

Analysis C2 will be completed in the following manner. By the end of the second year, deep-sea cores will be reviewed and selected, and a decision made on the need for additional cores. These cores will be obtained and analyzed in the following 2 yr. The sea surface temperature reconstructions will be completed, and the results will be reviewed by the end of the fifth year of study.

8.3.1.5.4 Future climatic change investigation

This section provides a more detailed discussion of the analyses intended for future climate forecasts. It includes a discussion of the relation of these analyses to the issues identified in Section 8.2 related to climate change, discussion of possible future climate changes and their impacts upon the site, and the explanation of how site characterization will resolve the issues involving future climate changes.

This investigation will consist of one study having two study components. The first study component will consist of models of the local climatic variability within the region surrounding the Hanford Site repository. It

will consist of three separate analyses. The second study component will consider the global climatic controls upon the local variations in the next 100,000 yr and will emphasize the characterization of the next 10,000 yr. It will also consist of three separate analyses.

Three analyses will be done in support of the study component to model the variations in local climate within the region surrounding the Hanford Site. The first of these analyses will examine in detail the local climate variability itself. This analysis will produce a model to describe variations in temperature, precipitation, and windflow regimes within the immediate vicinity of the repository. The temporal and spatial resolution of model output will be defined by the needs of the groundwater studies and validation exercises. The second analysis will provide a model of growth of glaciers and ice sheets within the Pacific Northwest. These glaciers and ice sheets could directly impact the repository site or could lead to indirect impacts on that site. The third analysis will examine in detail one of these specific impacts of growth of ice sheets. This is the resultant floods that are derived from glacially impounded lakes. Such floods will be modeled in sufficient detail to describe the dynamic nature of flood waters within the Pasco Basin in order to estimate the impacts of these flood waters on the groundwater regime and on erosion and deposition within that area.

The second study component within this study will concentrate on estimation of the global climatic controls on local climatic variability within the Pacific Northwest. It is anticipated that a number of global climatic changes will occur over the next 100,000 yr that could impact the stability of the repository. In order to predict the timing and probability of these events in a manner that is consistent from site to site, the DOE has separately commissioned the study component of the global climatic changes. Three separate model procedures will be developed in order to estimate the timing and the magnitude of global climatic changes. The first analysis will consider a set of global drivers that describes the timing and probability of events on a very crude scale. The second analysis will consider the details of ice sheet growth on a global basis that can impact a global climatic system. The third analysis will make use of the boundary conditions provided by the other two global models in order to estimate in greater detail the regional climatic response to this global change. That regional response (i.e., data of cells from the global model that include the Pacific Northwest) will provide a set of boundary conditions that can be employed by the local climatic models to estimate the impact of climatic change on the repository itself. Each of these models is described in greater detail below.

8.3.1.5.4.1 Purpose and objectives

The purpose and objectives of this section are to project climatic variability into the future based on past and modern climatological conditions.

Predictions of future climate and certain climate-related conditions are planned to provide input information to studies that predict travel of radionuclides in groundwater, which in turn must demonstrate acceptable

exposure limits at the accessible environment. Six analyses will be required to forecast future climate of the Hanford Site and characterize the effects of changes of climate (Fig. 8.3.1.5-6). Three of the analyses were started in FY 1986 to ensure that the results would be available to meet the BWIP requirements.

8.3.1.5.4.2 Rationale for investigation

Analyses included in this section will create new and utilize existing mathematical and numerical models and the corresponding computer programs to allow forecasts of the future climate of the Pasco Basin and Columbia Plateau. Six distinct models are required for this purpose. They can be divided into two classes: (1) those for direct forecasts of local phenomena and (2) those for global controlling phenomena.

The first class comprises three models. The first model is of the local climate of the area and will be used for immediate application to the characterization of the stability of the Hanford Site (Analysis D1). A second, numerical model will represent variations in the cryosphere, especially the size of the Cordilleran Ice Sheet (Analysis D2). Both of these models will be linked to the forecasts of global climate change (Analyses E1, E2, and E3). The third model will define the characteristics of future catastrophic floods derived from glacially related lakes (Analysis D3). This model will be linked to the models of local climate (Analysis D1) and glaciation (Analysis D2).

The second class of models comprises three models for forecasting global components of the climate system that influence local climate: (1) the general status of the global climate over the next 100,000 yr will be determined from the driver model, which will consider factors such as the influence of changes in the orbital parameters of the earth on the global ice configurations (Analysis E1); (2) a two-dimensional, dynamic model of ice dynamics, coupled to an energy balance model, will provide an estimate of the global configuration of ice sheets at regular intervals in the next 100,000 yr (Analysis E2); and (3) an atmospheric general circulation model will forecast broader regional changes within the global context (Analysis E3). The behavior of oceanic circulation systems, and the correlative changes in sea surface temperatures, will be coupled in the atmospheric general circulation model.

These model analyses differ from the study components of the past climatic change investigation (Section 8.3.1.5.2.3) because they are specifically designed to produce forecasts of the future climate of the area. The analyses that are required to characterize the future climates of the area are grouped into a single study. Even the cursory description provided in the previous paragraphs highlights the interdependence of these various analyses. This interdependence is illustrated in Figure 8.3.1.5-3.

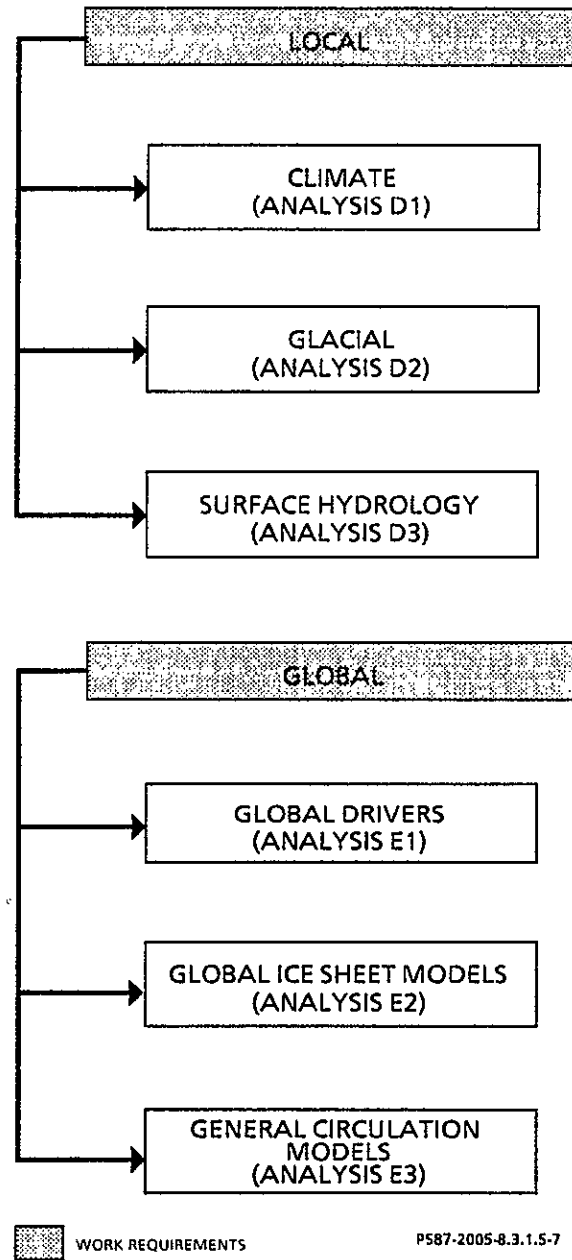


Figure 8.3.1.5-6. Work requirements and analyses included in the forecasts of future climates.

The key item in models of future climatic variations is the local climatic model (Analysis D1). Analysis D1 will characterize future climates directly. Results of analysis D1 will also be used to specify the bounding scenarios to allow modeling of future groundwater systems. Results of the local climate model will be used to specify external controls on the growth of the Cordilleran Ice Sheet at its southern margin (Analysis D2). Ice sheet growth will control the extent of isostatic effects of the glacier (on the regional stress field) and will control the timing and magnitude of glacially derived catastrophic floods (Analysis D3).

Before the local climatic model can be used for forecasts, it must be linked to the more global descriptions of climatic change (Analyses E1, E2, and E3). The quality and reliability of the local climatic model must be tested by its ability to reconstruct the modern climate as well as the paleoclimate record. Thus, the need to test the local climate model (Analysis D1) strongly controls the timing of the other studies.

8.3.1.5.4.3 Description of future climate change study

The following sections provide a more detailed discussion of the analyses that are included in the study of future climate change. Three analyses are included in each of the two study components. The descriptions that follow are not intended to be a comprehensive discussion of the analytical procedures that will be followed. Rather, they are intended to describe general details sufficient for someone versed in the methodology to understand the intended procedures. Exact details of each of these analyses are provided in the study plans as a separate document.

In this section the terms model, mathematical model, numerical model, computer code, verification, and validation are used in the sense of NUREG-0856 (Silling, 1983).

8.3.1.5.4.3.1 Study Component D: future local climatic change.

8.3.1.5.4.3.1.1 Analysis D1--Construction a local climate model. The central focus of the entire future climate study is to provide estimates of the characteristics of future climatic regimes at the proposed repository site. This analysis will result in a computer-based model that is expected to describe the climate of the area at a set of points equally spaced over the region of interest (at least the Columbia Plateau geohydrologic system). These forecast values will consist of the temperature, precipitation, evapotranspiration, windflow patterns, and runoff. Runoff will be characterized in such a way that streamflow in the area will also be estimated. Information provided in this analysis will be used to specify bounding conditions on recharge to the regional groundwater system for use in sensitivity analyses, as described in Section 8.3.1.3.

The information provided by Analysis D1 will include estimates of the long-term characteristics of climate that will satisfy Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Items 1 and 2). This will include these required estimates of the "potential maximum and minimum changes and rates of change in

precipitation and air temperature from the present time" and "potential regional windflow and precipitation patterns that may evolve in the future as a result of climatic and geologic changes."

Limitations and alternatives to this approach (a statistical model) have been described in Chapter 5 and are summarized here. Before the results of using the local climate model can be defended as a reasonable forecast of future climate, it is necessary to subject the model, and model results, to a careful and thorough scrutiny. From such an assessment, quantitative measures of the accuracy and precision of the model will be produced. Based upon the results of tests of the model as well as theoretical arguments, specific situations in which the climate 'extrapolations' are weak or unreliable will be identified. The availability of this information will satisfy the Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2) guidelines for evaluation of the capabilities of the models used.

The BWIP is currently considering alternative approaches to the method of estimating local climate change (Analysis D1). Two different types of modeling methods are known and are being considered: (1) statistical relations (Craig and Roberts, 1984; Klein, 1985), and (2) physical principles (Pielke, 1984). Both methods will be investigated for the most appropriate application for climate change on the Hanford Site. Some characteristics of each of these model types were discussed in Section 5.2. Presently the BWIP will proceed with the statistical approach, and the discussion that follows is based on that assumption. If that changes, other study plans will be affected. It is expected that the BWIP will convene a meeting of experts on such modeling during the first year of the study to fully consider the range of modeling approaches that are possible and the strengths and limitations of each. If another model method is considered more appropriate, future SCP updates will reflect the different model approach.

Disadvantages of the use of a model based upon physical principles are discussed next. A wide range of such models exist (Section 5.2). The most sophisticated of these are the primitive equation mesoscale models. It is assumed by the BWIP that, of the physically based models, these represent the ones most likely to succeed in the studies that are required for site characterization. Thus, the comparative evaluation is confined to a consideration of the potential value of these models with respect to statistically based models.

Mesoscale models are relatively new and are currently under extensive development at a number of research institutions (Pielke, 1984). All existing models are designed to model meteorologic phenomena, such as individual storms. Typical integration times are several days and the useful skill of such models is confined to such short periods. They are not currently designed to, nor used to, simulate "climate." No example of such a simulation of modern climate that has been tested against a real situation is known to the BWIP. One, untested, example of simulation of a simple modern climate scenario is given by Pielke (1984). Thus, to make use of such models would require application in an essentially untested field that is expected to require a number of years of effort, which would not be of direct benefit to the BWIP.

As would be expected, since the mesoscale models are not generally used for study of climatologic problems, there is no experience with their application to the study of paleoclimates. It appears impractical and ill advised to undertake such an application until such time as mesoscale models can be shown to regularly produce successful forecasts of modern climate. Even when that has been achieved, it must be assumed that several years of application to paleoclimatologic problems would be required before it would be reasonable to conclude that they can be expected to be successful at that on a regular basis. Only at that time could application to forecasting even short-term (100 yr) climatic changes be undertaken on any but a purely experimental basis.

Mesoscale models are extremely expensive to solve. They are computationally intensive programs that usually require the use of a "super-computer" such as a CRAY or a CYBER. Thus, experimentation, development, and final application require considerable time and resources. It is difficult to speed the research. For this reason, it is not anticipated that the required development and validation can be achieved in time to satisfy the programmatic needs of site characterization.

Mesoscale models are not, at present, complete representations of the physical processes. Certain processes are represented within the model by parameterization. This commonly involves the estimation of parameters values from empirical data using statistical methods. Thus, the same limitations of statistical models as discussed earlier may apply to these models. Processes that are parameterized within mesoscale models include two that are very important to the BWIP site characterization: precipitation and evaporation. Accumulation of snow may not be represented at all, depending on the model chosen; if it is, it will be parameterized. Whether the parameterizations of a given model could be useful to the BWIP site characterization would have to be investigated on a model-by-model basis and such validation could be prohibitive.

Mesoscale model grid resolution is generally too coarse for application to site characterization. It is expected that resolution of a few kilometers may be needed. This resolution is not available on most, if not all, mesoscale models without violation of an important modeling assumption (the hydrostatic assumption). There is insufficient experience with the use of such models at very fine resolution to warrant their use at fine grid scales without extensive testing. In regions of high relief, such as the Cascade Mountains, and where corrective atmospheric motions are strong (such as the Columbia Plateau), the hydrostatic assumption can be a poor approximation to the real atmosphere.

No mesoscale model has yet been applied to the description of weather (or climate) along the edge of an ice sheet. An ice sheet is expected to be within the area of concern during the next 100,000 yr. To describe the relevant processes would require new parameterizations, and the available data base for this is extremely limited (as was pointed out in the discussion of problems with the use of a statistical procedure). To develop, validate, and

9 2 1 2 5 5 5 0 2 3 7

apply such a computational procedure would require considerably more computational resources than using a statistical method. For these reasons, a mesoscale model is not considered desirable for the BWIP site characterization.

At the present time a feasibility study is being undertaken by the NNWSI and the BWIP will keep informed about the results of such a study and will reassess the program when those results are available.

The local climatic model (Analysis D1) will be an empirically based set of regression equations that relate variables (independent) describing regional controls on climate with the variables (dependent) representing the climate (mean temperature and precipitation, and possibly other variables). The independent variables will be limited to those that can be reconstructed from the geologic record or predicted from global models using currently available techniques (e.g., topography, sea surface temperatures, and dominant wind velocities).

Variables derived from these basic data will also be considered. Examples of these derived variables include distances to topographic highs and lows, changes in elevation along a dominant wind direction, and variations in coastal configuration due to sea level changes.

Multivariate regression procedures will be used to parameterize the equations from modern climate data (standard climate). Computer codes will be constructed to apply the resulting equations to the entire Columbia Plateau. This will allow testing the equations over a broad range of observed climatic conditions.

Some difficulties and limitations of the regression approach include the following. Such a model can only be expected to be accurate for the same range of independent variables from which the model was originally developed. It may retain its accuracy over a larger range of independent variables; however, when the input parameters fall outside of the range of the data used to construct the model, nonlinear effects can cause the regression estimate to be in serious error. To ascertain whether such nonlinear effects actually occur, it is important to test the goodness of fit of the model against independent data sets that represent a greater range of independent variables than were used to construct the equations. Ideally, these tests would cover the entire range of independent variables over which the equations will be applied for forecasts. In this case the difficulties of nonlinear effects can be shown to not influence the answers obtained. For this reason, extensive testing of the local climate model against independent paleoclimatic reconstructions is important.

If the local climate model can be certified to produce acceptably accurate estimates of modern climate, it will be applied for reconstructions of paleoclimates. A very extensive set of tests will be conducted, because the ability to reconstruct paleoclimates forms the basis for extrapolation to future climate. Although tests, per se, are not possible relative to future climates, the reasonableness of the forecasts will be reviewed by scientists

having the appropriate expertise. To ensure that the local climate model extrapolations are reasonably constrained, the parameters will be examined over a range considered likely to occur in the next 100,000 yr, based upon the record of the Quaternary and expected fluctuations in driving factors.

In addition to standard statistical evaluations, tests of the local climate model will consider its ability to reproduce climatic and paleoclimatic observations as well as certain derived variables, including runoff, streamflow, lakes, glaciers, and vegetation patterns. The tests will cover the range of values typical of the late Quaternary.

8.3.1.5.4.3.1.2 Analysis D2--Simulating the growth of glaciers. During major climatic fluctuations throughout the Quaternary, extensive ice sheets developed over nearly all of British Columbia. At the peak of glaciation, these ice sheets extended into the northern part of Washington. Such ice sheets may have had an effect on the local climate of the Pasco Basin, including changes in the precipitation, temperature, windflow speeds and directions, and the surface hydrology of the system. Even more dramatic effects came during the abnormally large floods (exceeding the 1,000-yr return period flood), which resulted from the failure of ice dams. Large volumes of water were released that had been held in proglacial lakes, such as Lake Missoula. At least one major flood passed down the Snake River due to overflow from glacial-age Lake Bonneville.

Simulating the growth and decay of glaciers is also important from a tectonic and geomorphic standpoint. For example, isostatic depression and forebulging associated with ice advance and retreat could increase fracturing and (or) seismicity in the area of the repository (this problem is discussed in greater detail in Section 8.3.1.2). Another adverse scenario is proglacial aggradation during ice retreat that could deposit outwash plains in the Pasco Basin leading to the diversion of the Columbia River into the Cold Creek syncline.

These are not isolated events, but are all manifestations of the important influences that glaciation can exert on the region. Future glacial events can be expected to reproduce these same phenomena. It is quite likely that such glaciation will occur, perhaps more than once in the next 100,000 yr. Thus, it is essential that the influences of such glaciations be accurately described and forecast. The purpose of this analysis is to produce a numerical computer model of glacier dynamics that will accurately represent the characteristics of glaciation in the region. This will allow an assessment of extreme future limits of glaciation by the Cordilleran Ice Sheet and its significance. The glaciation model will directly forecast certain of the glacially related phenomena and provide input to another model that will consider the more indirect effects of floods.

The glaciation model (Analysis D2) will provide the basis for estimates of the long-term "fluctuations in...[the] cryosphere due to climatic changes." Such estimates are requested by Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Item 4). Results of this model will also contribute to the estimates of the "severity of glacial regimes in the site area" as are

requested to satisfy Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Item 3). The information about glacier configurations at various stages during glacier growth will be used as input to the general circulation model studies described in Analysis E2 below.

Ice dynamics within the Cordilleran Ice Sheet (Analysis D2) will be modeled using at least a two-dimensional (spatial dimensions) mathematical model based on the general flow law for ice. These equations will be supplemented by the equation of continuity for unsteady flow. Sliding at the base will be represented using previously developed relations with basal shear stress and roughness as summarized by Paterson (1981). The possibility of surging will also be represented (McInnes et al., 1985).

Thermodynamic variations may be modeled, as will changes in ice density (Jenssen, 1977). A three-dimensional mathematical model (Grigoryan et al., 1976) will be applied if preliminary assessment determines that it is necessary. Finite difference procedures will be used to obtain a numerical approximation of the solutions. Discretization and solution methods will closely parallel those used for the modeling of glacially derived floods.

Since the exact form of the equations to be applied has not been established, it is not possible to state the assumptions involved in the ice flow model. Regardless of the exact form, it must be assumed that the general form of the flow law is correct (Glen, 1955). The flow parameter, A , is known to vary with temperature, crystal size, crystal orientation, and content of impurities. Because this dependence cannot be parameterized, it will be assumed that the influence of these factors will be represented by the mean value of the parameter used (Paterson, 1981). Estimates of the flow parameter will include the influence of hydrostatic pressure. Its dependence on the activation energy may not be represented if the form of the relation cannot be specified.

It will also be assumed that the strain rate is related to the stress deviator components through a constant of proportionality, λ . This assumption is only approximately true as λ is known to be a function of position in the glacier (Paterson, 1981). Additional assumptions likely to be required to obtain a solvable mathematical model are that the normal strain rates are negligible compared to the shear strains and that the bed of the glacier is of low gradient and not very rough. Methods to avoid these assumptions will be investigated, because they are only poorly satisfied for the Cordilleran Ice Sheet.

Parameters for the flow include the bedrock topography and mass balance of the glacier resulting from ablation, calving, and accumulation. To the extent practical, the latter will be specified from output of the atmospheric general circulation and local climate models (Analyses E3 and D1, respectively). Initial conditions that must be specified include the thickness of the ice at each point and corresponding sliding velocities.

Input requirements for this ice flow model will include the topographic configuration of the area specified in grid format, coastline configuration,

and climatic conditions (temperature and precipitation amount and form). Initial conditions will usually be considered as ice in its present configuration. Alternative initial conditions will be specified to test the ice flow model against the paleoclimatic and geologic records.

Verification of the ice flow model will be achieved primarily through its ability to solve more simple problems for which analytical solutions are available (Silling, 1983). A large number of such examples exist (Paterson, 1981, p. 153-161). Validation of the ice flow code will be achieved through comparisons of the prediction of the model to the actual geologic record when supplied with initial and boundary conditions representative of these times.

Benchmarking of the ice flow code can be done through comparisons of the solutions obtained when the model is applied to other locations that have been modeled previously. Examples include the Laurentide Ice Sheet during the latest glaciation (Andrews and Mahaffy, 1976) and the Barnes Ice Cap on Baffin Island. Comparisons to other models of the Greenland and Antarctic Ice Sheets may also be possible (see, for example: Budd et al., 1971; Radok et al., 1982).

8.3.1.5.4.3.1.3 Analysis D3--Modeling the dynamics of major floods. It is known that major cataclysmic floods affected the Pasco Basin during the Quaternary. The same topographic configuration and drainage system organization that was responsible for such floods still exist. Such conditions are also likely to be coupled with the requisite climate change to produce more floods in the future. Therefore, it is important to assess the likely impacts of recurring flooding. One possible impact of large floods such as those which have derived from Lakes Missoula and Bonneville is extreme water depths in the Pasco Basin. During at least one Missoula Flood, waters reached 350 m (1,150 ft) within the Pasco Basin (Baker, 1973). This would produce a depth at the 200 Areas within the Hanford Site of about 150 m (492 ft). The depth may have been greater depending on the amount of unconsolidated sediment removed by the flood before the high water mark was reached. Such a depth of water may have been enough to create sufficient water pressure upon the basalts to lead to enhanced recharge (i.e., pressurized recharge). Analysis D3 will evaluate the recurring flood characteristics and produce an estimate of the likely impacts of such floods on the surface hydrology of the Pasco Basin.

To examine the possibility of pressurized recharge and other impacts of extreme floods upon the site, an analysis of the dynamics of such floods will be performed. Information about depth and duration of these extreme flood events within the Pasco Basin derived from this analysis will be supplied to the analysis of flood effects upon the groundwater system and radionuclide transport (see Section 8.3.1.3).

The mathematical model of dynamics of Lake Missoula floods (Analysis D3) consists of the momentum equations and mass continuity. These will be solved for the two spatial dimensions using the unsteady flow formulation. It is anticipated that a Crank-Nicholson semi-implicit, finite difference representation will be applied (Burden and Faires, 1985, pp. 586-589). The

finite difference grid will be based on the alternating direction implicit method (Wang and Anderson, 1982, pp. 103-107). Time-step length may be varied at each time step to minimize the computations, subject to the appropriate stability constraints.

The two-dimensional formulation is based on the assumption that the results of interest are insensitive to changes in the third dimension. It is assumed that the flow is incompressible and that the friction factor can be expressed with the Chezy-Manning equation. Manning's "n" (a measure of friction) will be modeled separately for each grid cell. Computation of the gravitational term will carry with it the implicit assumption that all channel slopes are low, less than about 10°.

Flow parameters include the channel topographic configuration and values of the friction factor. Initial conditions for the flow include the configuration of the lake and of the glacier margin and the possible existence of proglacial lakes in the flow path. Fluid kinematic viscosity may be considered time varying; if so, the initial value must be specified. Special handling of the time-varying conditions at the flow boundaries will be required during the expanding stages of the flood.

Input requirements of this flood model will include the boundary and initial conditions and parameters listed above. Both boundary and initial conditions will be perturbed to represent different flood scenarios. Such perturbations will be guided by the results of both the local climate model and the model of ice sheet dynamics. Further perturbations will be based on the possible modification of boundary conditions due to previous floods. Examples include the modification of topography from erosion and (or) deposition during such floods or changes in the configurations of proglacial lakes due to these prior floods. Inputs will also be perturbed to represent the range of uncertainty in these variables. Monte Carlo procedures will be used to summarize the effects of this uncertainty on the final results.

Selection of the exact form of the flow equations used will be based on considerations of the most general form of the relevant mathematical models. The full three-dimensional Reynold's equation, coupled with representations of surface stress due to winds, geostrophic forces, and energy balance terms, will form the starting point. Each term will be considered separately and geologic evidence will be reviewed to determine whether it is needed in the equation or can be ignored. Preliminary calculations will be made to estimate the magnitude of that term relative to others in the equations. This selection process will be guided by a panel of experts in the appropriate fields.

Where available, existing algorithms will be applied to flood behavior solution. Models of more limited applicability (e.g., one-dimensional models) will be used for computation of the appropriate segments of the flood problem. Results of these models will comprise a set of benchmarks against which the final model will be compared. Results of these benchmark procedures will be reviewed by a panel of experts.

Verification of the flood model (i.e., confirmation that it performs in the desired manner) will be achieved through tests against a set of specific computational tasks ranging from the solution of simple one-dimensional steady flow through the computation of higher dimensional problems with complicated boundary conditions exceeding the range of difficulty likely to be encountered in the actual modeling. Validation will be done through attempts to reconstruct specific examples of paleo floods that are well-documented from the geologic record. Such examples will have been produced as one end product of the paleoclimate reconstructions study.

Estimates of the uncertainty in each of the key variables will be based on the observed range of these values in single reconstructions from the geologic record and across each of the different reconstructions that have been done. Supplemental estimates of uncertainty will be based on expert judgment where sufficient data are not available. Together, these data will establish the acceptable limits of model performance in individual reconstructions. Tests (and improvements) will be continued until individual models are certified to reproduce the geologic record within this range of uncertainty.

Models will be run in Monte Carlo mode so that the full range of uncertainties in the parameters, initial conditions, and boundary conditions are represented in the model results. The distribution of the model results will be summarized statistically, and the summary statistics will be compared to corresponding estimates from the geologic record.

Informal, preliminary tests will be an ongoing part of the modeling effort. Formal, independent tests will be performed at the completion of each major modeling milestone. Test results judged to be unacceptable will require establishment of modifications in the modeling procedures. Planned modifications will be reviewed by a review panel before model incorporation.

These modeling analyses (Analyses D1 through D3) will result in computer code that is substantially new. In all of these analyses, preliminary model development has occurred. A more simplistic model of local climates has been developed for the southwestern United States with application to the potential repository at the Nevada test site (Craig and Roberts, 1984). Studies also have been completed on the flood dynamics of some of the catastrophic floods of concern (Craig and Hanson, 1986). These analyses have created a computer code that can form the basis of the BWIP computer codes. Relatively complete codes of ice sheet dynamics have been developed with application to other areas (e.g., Grigoryan et al., 1976). Such codes will be modified and adapted to the Hanford Site. Thus, in each case the basic modeling concepts have been formulated and a corresponding computer code exists. The BWIP analyses will focus on adaptation of those concepts and codes to the SCP. Procedures to be employed in these analyses are listed in Table 8.3.1.5-9.

Table 8.3.1.5-9. Procedures for global climate change local modeling study components

Procedure	Procedure
SMP-301	Determination of software classification
SMP-302	Software development specification preparation and approval
SMP-303	Final internal development review of computer code and documentation
SMP-304	Computer code acceptance testing
SMP-305	Computer code configuration control
SMP-306	Computer code and documentation change control
SMP-307	Computer code verification and (or) validation
SMP-308	Utility code documentation, control, testing, and use
SMP-309	Computer code application control
SMP-310	Magnetic media protection and control
SMP-311	Computer software transfer
SMP-312	Control of acquired data bases

8.3.1.5.4.3.2 Study Component E: future global climatic change.

Forecasting global climate change requires three different classes of models. These are (1) simpler global climate drivers that examine the time evolution of climate, (2) dynamic models of global ice sheet growth as a function of changing insolation, and (3) general circulation models that produce equilibrium simulations for specific boundary conditions. Procedures to be used in these analyses are listed in Table 8.3.1.5-9.

8.3.1.5.4.3.2.1 Analysis E1--Implementing global forecast drivers. Climatic change at the Hanford Site does not occur in isolation from the changes in the Columbia River Basin and the remainder of the Pacific Northwest. These regional changes occur in the context of global variations. This was certainly the case throughout the Quaternary when fluctuations on the order of the glacial-interglacial climate changes are considered (see Section 5.2). Thus, the regional climatic changes must be considered in the context of global climate. To forecast important changes at the Hanford Site, only those factors that can modify climate on a global scale will be considered.

Information from Analysis E1 will also be used to help satisfy Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Items 3 and 4). These items request long-term estimates of "the potential for glaciation, including estimates of times of onset of glaciation and lengths and severity of glacial regimes" and "future fluctuations in sea levels and cryosphere due to climatic change." Such estimates can only be accomplished if a global view of climatic change is employed.

The global forecast drivers program will identify those factors that can control global climate and for which reasonable representations of their variation can be made. The result of these models will be a sequence of "snapshots" representing expected climatic states at no greater than 1,000-yr intervals over the next 10,000 yr and a set of anticipated global climate scenarios over the next 100,000 yr, based upon these controlling factors. This information will be used to specify boundary conditions for the dynamic ice sheet models and the general circulation model analyses.

In global climate forecast drivers (Analysis E1), the key parameter is the volume of glacial ice present on the earth at a given time. Subsidiary variables will be considered to make this forecast, depending on the specific driver being considered. Global ice volume will be considered over the range of values believed to have occurred during the Quaternary. Tests of the global driver will be based on oxygen isotope records and other proxy climate indicators obtained from cores of oceanic sediments. Ratios of the isotopes ^{16}O and ^{18}O are considered to reflect the total volume of ice on the earth's surface at a given time.

At a minimum, the following models will be considered: (1) the Imbrie and Imbrie (1980) global ice volume forecast based upon orbital parameters and calibrated with oxygen isotope data; (2) the Hasselmann (1976) "red noise" model of climate change, which makes stochastic forecasts of global ice volume; (3) Pollard's (1984) model of ice volume linked to orbital parameters and glacio-isostatic effects; (4) the Kukla et al. (1981) astronomical climate index model; (5) an empirical spectral model based upon the observed spectrum of the oxygen-isotope ratio in the Northeastern Pacific Ocean; and (6) the Saltzman (Saltzman and Sutera, 1984) physically motivated model of the integrated climate system.

The character of the mathematical models differs from one conceptual model to another. For some, the mathematical models are based upon a differential equation expressing a relation between global ice volume and external forcing functions. Other climate models may specify only a general "climate state." Each model must be assessed and its strengths, weaknesses, and relative merits evaluated.

Computer algorithms will be defined to implement each model of global climate change chosen. Where appropriate, components of the climate system that are explicitly linked with the forecast (such as ice sheet mass balance or sea level changes) will be isolated. The process of selection and implementation of the models will be reviewed by the advisory panel.

8.3.1.5.4.3.2.2 Analysis E2--Modeling global ice sheet dynamics. The best known changes in the global climate system during the Quaternary accompanied the growth and decay of major ice sheets. These glacial-interglacial cycles have been shown to correlate with the variations in orbital parameters of the earth (precession, obliquity, and eccentricity) during the time (Hays et al., 1976). These insolation-controlled ice volume variations will be forecast most accurately in Analysis E1. In order to determine the effects of such ice volume changes upon the global climatic system, it is necessary to compute the actual configuration and extent of ice sheets at any given point in time that is of concern. Analysis E2 will provide the needed estimates of ice sheet characteristics.

These estimates will be produced through the use of a computer model based upon a two-dimensional, dynamic solution of the relevant equations of ice flow. Examples of such models are now in existence. One has been applied to the reconstruction of the dynamics of the Laurentide Ice Sheet for the last 100,000 yr (Budd and Smith, 1981). Such a modeling approach will be adapted to the computation of the global ice sheet system at sufficient spatial resolution to provide boundary conditions for the atmospheric circulation models to be used in Analysis E3.

Information from Analysis E2 will help to satisfy the request of Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Items 3 and 4), which calls for characterization of the variations in the cryosphere that can affect site stability.

The model that will be applied to estimate configurations of each major ice sheet on the globe at regular intervals of time during the next 100,000 yr will be based on methods like those described for the Cordilleran Ice Sheet (Analysis D2). Differences between the two include the application of finite element methods to the global model and the need in the global model for a more comprehensive computation of global isostatic deformation of the geoid due to loading by the ice. A coarser space and time step will be used for the global ice sheet computations, since resolution needed is defined by the very coarse grid of the atmospheric general circulation models.

Because the dynamic evolution of ice sheets is strongly controlled by variations in the mass balance, it is important to specify that mass balance as carefully as possible. To model future variations in mass balance, an energy balance model of the earth's climate system is being developed. This energy balance model may provide estimates of temperature and precipitation on a grid pattern over the globe. That information may be used to estimate glacier accumulation and ablation with greater precision than would be available with purely empirical estimates.

8.3.1.5.4.3.2.3 Analysis E3--Regional forecasting with general circulation models. The potential climate change at the Hanford Site must be considered as an integrated part of the global climate system. Regional boundary conditions must be specified to produce a forecast of local climate (Analysis D1). These include the patterns of atmospheric circulation, which

are dependent on sea surface temperatures, extent of permanent ice, atmospheric composition, and orbital variations. The model results are strongly dependent on the global heat balance and energy distribution.

One method of providing such information is the use of general circulation models of the atmosphere and, subsequently, fully coupled ocean-atmosphere general circulation models. Such models are now developed to a high level of sophistication at several large universities and national laboratories. The atmospheric general circulation models are routinely used to study modern climate and have also been used in a substantial number of analyses of climates of the geologic past (Kutzbach and Guetter, 1984; Manabe and Broccoli, 1984).

The information provided as a result of Analysis E3 will help to satisfy the NRC guidelines, which request long-term estimates of the "regional windflow...patterns that may evolve in the future as a result of climatic and geologic changes" (NRC, 1985, Section 5.2.2, Item 2). Solutions of the general circulation models are sensitive to the volume and distribution of glacial ice covering the earth as well as other geologic controls on the climate, including variations in the orbital parameters of the earth.

The numerical models currently used to study atmospheric and oceanic circulation (Analysis E3) are extremely complex and place heavy demands on computational power. Research personnel and installations will be determined and contracts will be signed at an early date so that needed results can be obtained in a timely manner.

General circulation models of the atmosphere will estimate a spectrum of variables for regional and global climates. Such models require a specification of boundary conditions (e.g., sea surface temperatures, ice extent, atmospheric CO₂ levels, surface albedo, and solar insolation). Since uncertainties exist in specifying or computing factors such as atmospheric CO₂ level or sea surface temperatures, the model simulations will be completed based on a sensitivity analysis of climatic response to a plausible range of variables contributing to global climate change. In terms of bracketing, model simulations will be based on the possible range of climate change over the next 100,000 yr. These models do not allow study of the evolution of climate as boundary conditions change. Except for representations of diurnal and seasonal insolation cycles, all boundary conditions remain fixed. For this reason the general circulation models merely represent "snapshots" of climate at a given time. Many such snapshots will be investigated.

A coupled ocean-atmosphere-ice general circulation model would provide a comprehensive representation of the climate system, thus ensuring that interactions between these climate components were included in simulating global and local climates. However, such models of the global climate with two-dimensional (spatial) horizontal resolution are not ready for applied experiments. Development of coupled ocean-atmosphere general circulation models is proceeding rapidly and should result in documented and well-tested codes by FY 1988. Such models are the preferable research tool, given

adequate computational time. Based on the computational expense, sensitivity experiments should be completed first on the more efficient atmospheric general circulation models. Bracketing potential future climatic change and guiding the types of simulations would be completed with the comprehensive models.

Models of the global climate will represent state-of-the-art capabilities. Since results of these global models must be used efficiently by the local climatic model, the exact methods used will be defined at an early stage, despite the fact that advances in those fields continue at a rapid pace. In the end, the quality of the forecasts might be less than would be achieved if such early selection had not been required.

Three distinct sets of computer code will be developed in this study component. For one of the analyses (Analysis E3), the major code elements already exist and have been used for many purposes. These are the codes for the global circulation models of the atmosphere and the oceans. At the current state of research in these fields, the two study components are being linked into a single model of global circulation. It will be preferable to use such a coupled model, if computationally possible, but these models are still under development.

A computer code for the global ice sheet model will be developed specifically for this project. It will involve a two-dimensional, dynamic equation and will be solved by means of finite element representation.

The computer codes for the global forecast drivers (Analysis E1) will be written specifically for this analysis, although certain of the methodologies have been explored in applications to the Hanford Site defense waste studies and the Nevada Nuclear Waste Storage Investigations.

It is anticipated that the Community Climate Model at the National Center for Atmospheric Research will be used for the atmospheric modeling. The most recent developing version of the Community Climate Model includes an oceanic circulation component. This version is preferable for later analyses to ensure comparable results. Design of the Community Climate Model (or any other atmospheric general circulation model) runs requires careful specification of the boundary conditions.

Most atmospheric general circulation models are computed in the spectral domain (Simmons and Bengtsson, 1984). Thus, it is necessary to transform the boundary conditions to the spectral domain before processing. Analyses for equilibrium conditions and fixed insolation are typically continued through at least 300 simulated days. Results are averaged for only the final 200 d; the first 100 d represent the equilibration period. More complex boundary conditions of seasonal insolation are simulated with runs that can extend for several years. It may be desirable to make use of such seasonal cycle simulations in order to evaluate moisture balance in the hydrologic cycle.

9 2 1 2 5 5 0 2 9 8

Boundary conditions for runs of an atmospheric general circulation model include the locations of continental areas and their elevations, the location and elevations of continental ice, the location of sea ice and its temperature, surface albedo, and the sea surface temperatures. These values are specified on a latitude-longitude grid at a spacing of about 4.5° by 7.5°. Reconstructed data will be derived from data gridded at a spacing of 2° by 2°. For paleoclimatic conditions, much of these data will be available from the CLIMAP project (CLIMAP, 1976; 1981). Another important boundary condition is the insolation regime of the earth. This is readily computed from the orbital parameters of the earth for the time periods of interest (Berger, 1978a). Current solutions are computed at 1,000-yr intervals of time. It will be necessary to compute solutions at shorter intervals of time if greater resolution of estimated rates of climate change are found to be needed by the groundwater modeling exercise. For each of the various types of boundary conditions, the selection of values is based on the particular time horizon represented (when analyzing for comparison to the geologic record) or the specific scenario being considered (for the future climate analyses).

Existing published model results for the last glacial maximum will provide a set of benchmarks in the early stages of the project. Some examination of the validity of the model results can be obtained from the comparisons to the various time horizons represented in the geologic record.

One potential difficulty with the coupled general circulation model being considered is the coarseness of resolution of sea surface temperatures that would be computed. This coarseness limits the ability to represent the importance of changes in currents in the northeast Pacific Ocean. This question must be examined in greater detail as the coupled model becomes available for application.

For the super-interglacial conditions, high atmospheric CO₂ will be incorporated and sea surface temperatures will be derived from published estimates from seasonal, interactive mixed layer general circulation model experiments. Since the DOE is currently performing extensive analyses of the CO₂ problem, there will be an attempt made to collaborate with the DOE Carbon Dioxide Research Division in the specification of realistic bounding scenarios for the super interglacial.

Verification, validation, and benchmarking of the computer codes and mathematical and numerical models will follow NRC guidelines for documentation of codes (Silling, 1983). The basis of these efforts will be an examination of the ability of the coded procedures to accurately reproduce the modern circulation patterns and those reconstructed for both the last glacial maximum and other time horizons (where data are available). All model results will be reviewed by an independent panel of experts at regular intervals during the characterization process.

The computer code for the global climate drivers will be based, whenever possible, upon an existing code(s). These codes will be combined into a single computer program to facilitate their use and to ensure consistency in the implementations. A new code will be prepared for specific models when an appropriate code is not available.

For Analysis E1 the character of the mathematical models differs from one conceptual driver model to another. For some, the mathematical models are based upon a differential equation expressing a relation between global ice volume and external forcing functions (e.g., Imbrie and Imbrie, 1980). Other climate models may specify only a general "climate state." The most detailed models provide estimates of the global ice volume.

8.3.1.5.4.3.3 Contingency plans for modeling.

An important question that should be addressed is the possibility that model validation will result in the conclusion that one of the component models is unacceptable. Some alternative strategies should be defined for each of the models and a preliminary assessment of the probability of success is of interest. The BWIP has undertaken an exercise to consider this question and the results are summarized as Table 8.3.1.5-10. Six model components are to be employed.

Table 8.3.1.5-10. Estimated likelihood of success of model components and alternative strategies

Analysis	Model(s)	Probability of success	Alternative model(s)
D1	Local climate	0.70	Mesoscale physics climatological extremes
D2	Cordilleran Ice Sheet	0.70	Ice sheet without full topographic control (Mahaffy, 1976)
D3	Extreme floods	0.70	Empirical estimates
E1	Global drivers	0.85	Many are being considered; all currently are useful
E2	Hemispheric Ice sheet dynamics EBM	0.70	Budd and Smith (1981) North et al. (1983)
E3	Fully-coupled GCMs	0.70	Mixed layer GCMs
	Mixed layer GCMs	0.80	Fixed SST GCMs
	Fixed SST GCMs	0.90	EBMs

EBM = Energy balance model.

GCM = General circulation model.

SST = Sea surface temperature.

Estimates of the probability of success are subjective and based upon prior experience with these types of models. Analysis D1 will be based upon a model already developed and applied to paleoclimates in the southwest. Analysis D2 will require addition of computations of topographic effects to an existing model. It will also make use of an existing energy balance model for further development. Analysis D3 involves improvements to a model that currently exists. Analysis E1 will employ models that already exist. The probability estimate is based on a published estimate of percent variance in common. Analysis E2 does not require a major new model. The application to all hemispheres simultaneously is new. Analysis E3 will make use of three models that currently exist. All but the fully coupled model have been applied to paleoclimatic problems.

Any of these models could fail to provide acceptable answers. In this the term "failure" will be applied to models that consistently produce results that are significantly different than modern and paleoclimatic test cases. Consistent discrepancies are required to judge a model failure since the paleoclimatic reconstructions themselves could contain errors. Final decisions as to whether a model is acceptable will be based upon the recommendations of the appropriate advisory panel in light of the validation results.

In the event that a model is determined to be unacceptable, the alternative models listed in Table 8.3.1.5-10 will be considered. In general, these alternative models have disadvantages. Most offer a higher probability of "success" but at a greater cost of time or effort and the "success" is more apparent than real. This is because the alternatives usually provide lower resolution and therefore cannot be tested as thoroughly. This lower resolution also means they will be less useful for satisfying site characterization information needs.

8.3.1.5.4.4 Application of results

All of the analyses in the investigation of future climates will produce information that will become a part of the performance assessment. Certain of these analyses will provide direct input; the others provide indirect support (see Fig. 8.3.1.5-3). Modeling of future climate is important to tectonic and geomorphic studies also (see Section 8.3.1.2). Specific uses of these results are described below.

From the local climate model (Analysis D1) will come a set of scenarios that describe the possible and most probable climatic states expected at the Hanford Site throughout the forecast period. Variables specified include temperature, precipitation, evapotranspiration, and wind velocity. These will be specified on a detailed grid to illustrate the spatial variability of these factors. Recharge to the groundwater system will be computed from this information and this will form bounding values for models of the groundwater system. The impact of climatic change upon the geohydrologic system will thus be estimated. This model will also provide input to the other analyses in this component, including glaciation (Analysis D2) and floods (Analysis D3).

Results of the modeling in Analysis D3 (glacial age floods) will form a portion of the performance assessment. Site stability during such floods in the future will be described and the specific impacts of such floods will be reported. Such an assessment is requested by Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2).

Results of the glaciation model (Analysis D2) will be reported in the SCP updates. This will satisfy a portion of Regulatory Guide 4.17 (NRC, 1985, Section 5.2.2, Items 2 and 3). This glaciation model will also provide input to the local climate model (Analysis D1), the Missoula floods model (Analysis D3), and the general circulation model runs (Analysis E3).

Results of regional forecasting with general circulation models (Analysis E3) will provide input to Analyses D1 and D2. Primary input will be boundary conditions required for these other models. For the local climate model (Analysis D1), regional wind patterns will be used. The means of linking general circulation model winds, temperature, and hydrologic balance will be investigated. The ice model (Analysis D2) will use temperature and precipitation from the general circulation model output.

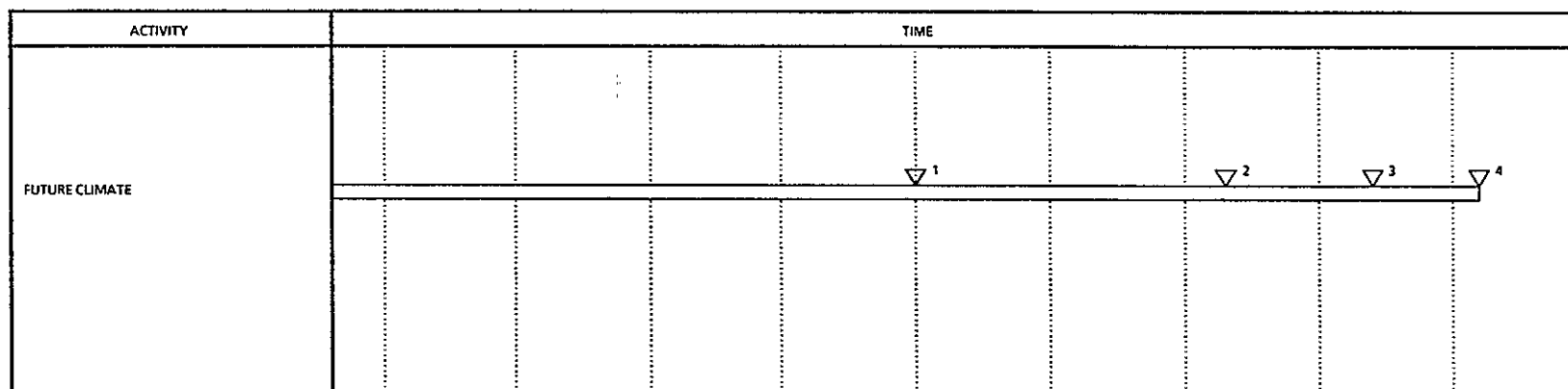
Forecast drivers (Analysis E1) will provide input to the design of general circulation model runs in Analysis E3. This analysis will also provide specification of the global climate state (1) controlling glacial growth in Analysis D2 and (2) controlling the local climate state in Analysis D1. Analysis E1 will also provide a general statement of the range and sequence of climate change expected at the site that will be reported directly in the performance assessment report.

The configuration of the major global ice sheets at specific times in the future (Analysis E2) will allow specification of boundary conditions required for the solution of the atmospheric circulation (Analysis E3). The dynamic behavior of the ice sheets during this period will form the basis of an estimate of the probability of climatic changes that could affect site stability. This will be important information for the calculation of anticipated and unanticipated events.

8.3.1.5.4.5 Schedules and milestones for investigation

Figure 8.3.1.5-7 shows the schedule and selected milestones for the future climatic change investigation. The following discussion of the schedule assumes the results of the sensitivity study to be conducted by the end of the third year of study support detailed climate analyses. Study scope and, hence, schedule could change if the outcome of the sensitivity runs do not support exhaustive climate analyses.

Constructing the model of local climate (Analysis D1) will begin in the first year of study with definition of the model structure. Work completed in the third year will consist of compilation of the available climatic, topographic, and ocean temperature data sets and an initial definition of tests of the model. By the end of the fourth year, the form of the model will be identified and parameters will be estimated, as well as a definition of



- ▽¹ EVALUATION OF STUDY SCOPE BASED ON SENSITIVITY ANALYSES.
- ▽² DEVELOP DISRUPTIVE SCENARIOS.
- ▽³ FUTURE CLIMATE FORECASTS.
- ▽⁴ COMPLETED FUTURE CLIMATIC CHANGE INVESTIGATIONS.

PSSB-2014 8.3.1.5.3

Figure 8.3.1.5-7. Schedule and selected milestones of the future climatic change investigation.

the tests of the model's ability to reproduce both modern local climates and paleoclimates. Such tests will include, among other things, tests of estimates of the surface hydrologic balance. Work completed in the sixth and seventh year will include testing of the model's ability to forecast modern local climate, tests of the paleoclimate forecasts, actual tests of the modern predictions, and paleoclimate reconstructions. By the end of the ninth year, forecasts of the future climatic conditions at the site will be completed and reviewed by an independent panel.

Simulating the growth of glaciers (Analysis D2) will begin in the first study year with a review of the existing ice dynamics models. The conceptual model that (1) defines the model components produced, (2) describes the connections and interactions between the various study components, and (3) identifies the mathematical structures employed will be completed, and model structure will be reviewed by a panel of experts. After it is certified by the panel, the model will be implemented as a computer code by the end of the fourth year. During the sixth year, the model will be tested and, after acceptance, will be used to model the behavior of ice sheets during glacial episodes--as forecast from the model of global climate change (Analysis D1). In the sixth study year results will be compared with the global ice sheet model. By the end of the seventh study year, the model will undergo testing and external review.

Modeling the dynamics of major floods (Analysis D3) will also begin in the first year with specification of the form of the equations used for this analysis and the variables needed. By the end of the next year, the numerical solution procedure will be defined. The computer code will be created by the end of the following year. The code will be tested by the end of the sixth year. In the seventh study year, paleoflood dynamics will be reconstructed. In the following year the results of the analysis will be made available to hydrogeologists. These results will form bounding scenarios for appropriate groundwater flow models.

Implementing global forecast drivers (Analysis E1) began in FY 1986. During FY 1987, appropriate personnel at the other repository sites will be contacted, and an attempt will be made to establish a cooperative arrangement. The appropriate panel of experts will be identified and convened to organize the various components of the work. Review of the literature will begin. By the end of FY 1987 the literature review will be completed. Also, the models to be used will be determined. In the following year, computer code for these models will be completed, and the drivers will be implemented. During the next year, review of the code and results will be completed. Comparisons between the various model forecasts and selection of a representative set of climatic change scenarios will be completed by the end of the fourth year of study. The drivers will be tested and scenarios evaluated in the fifth year of study. Preliminary general circulation model results will be used to select scenarios in the next year. In the seventh study year, the Pacific spectrum will be used for error estimation.

During FY 1987 a finite element form of the solution of the two-dimensional equations of dynamic ice flow will be defined (Analysis E2). In

the following year, this will be used to reconstruct the history of the Laurentide Ice Sheet as a test of the model. One year later, the model will be applied to the reconstruction of all major ice sheets, and the definition of methods of linking the model to the drivers defined in Analysis E1 will begin. This work will continue through the next year. In the fourth year, the means to link the ice sheet model to estimates of future global driver forecasts will be completed and reviewed. Actual forecasts of future ice sheet configurations for the next 100,000 yr will be completed during the following year. Links to the driver to model future ice will be defined in the sixth year, allowing future ice sheet scenarios to be modeled the following year.

Regional forecasting with general circulation models (Analysis E3) will proceed in the following manner. By the end of FY 1986, preliminary contacts with the appropriate research organizations and organization of the panel of experts had been made. Review of the current state of knowledge in numerical modeling of oceanic circulation and consultation with experts in the field to determine the advisability of using ocean circulation models for this purpose was also completed at this time.

During the first year of study, the following work will be completed: a review of the existing record of atmospheric general circulation model runs and identification of current plans for additional runs; determination of major gaps in the available collection of atmospheric general circulation model runs; determination of experiments to bracket possible climatic change and to characterize limitations; and the initiation of needed additional run specification. First additional runs will begin. In the second study year, definition of the runs to characterize future climates will be required. Future climate will begin. If it is determined that such modeling is appropriate, the selection of the procedures used and the definition of the specific scenarios investigated will be completed.

The following work will be completed in the third year: additional sensitivity runs will be made as required; results will be made available to local climate model; summarization of the results of the various runs will be made as they become available; determination will be made of specific past and future time slices and high-risk conditions for the second stage of general circulation model modeling.

Links to global drivers and the ice sheet model will be defined in the fourth year. By the end of the following year, two more tasks of Analysis E3 will be completed: (1) testing of general circulation model (if available) for coupled atmosphere-oceanic circulation and using the model to produce forecasts of oceanic conditions in the northeast Pacific Ocean and (2) completing most of the simulations used to characterize specific times and high-risk conditions. Results will be made available for use in the local climate model. Panel review of these results will be made, at which time modifications of the plans may be made as required.

Work completed by the end of the sixth year will consist of final general circulation model runs, if necessary. Also, summarization of the results and

panel review will be completed. Future general circulation model scenarios will be prepared in the following year. Finally, the final results will be incorporated into the local climate model.

Three types of documents will be provided from each of the modeling analyses.

1. The first category consists of the output of the model as it will be used in other modeling analyses. This output will be provided in both hard copy and in computer readable format. A report, summarizing the results of the analyses using the model, will be produced for each of these models.
2. A second type of document will be the final report on the entire analysis itself. This will summarize the various steps of the analysis and the conclusions reached from its use. This document will form the basis of the relevant portions of the performance assessment document.
3. The third type of information produced (for each analysis) will consist of the five documents required by NUREG-0856 (Silling, 1983).

The categories of documentation are as follows:

- Software summary.
- Description of mathematical models and numerical methods.
- User's manual.
- Code assessment and support.
- Continuing documentation and code listings.

Continuing documentation and code listings will occur on a semiannual or annual basis, as appropriate, and will continue until a final selection of a repository is made.

8.3.1.5.5 Site meteorology investigation

Atmospheric dispersion and meteorological conditions at the Hanford Site must meet certain criteria (as detailed in Section 8.2.2.2) for the site to be acceptable as a geological repository. Meteorological data and analyses are required to determine if these criteria are met and to provide additional information for site planning, construction, and operation activities. Where the existing meteorological data base provides insufficient data to meet objectives, additional data must be collected. Likewise, additional analyses are required where existing studies do not adequately characterize certain parameters or conditions. Fortunately, an intense program of meteorological monitoring and data analysis has been ongoing at the Hanford Site since 1944 (some data collection began as early as 1912), providing a detailed meteorological data base and published studies that should provide much of the

meteorological information required to address repository issues. In addition, a number of meteorologic studies are planned to support Hanford Site activities that are not associated with the repository project.

A characterization of the recent climate of the site, a discussion of the existing meteorological data base, and a description of the monitoring program are presented in Chapter 5, Section 5.1. A more detailed presentation of meteorological data and a description of past and ongoing programs are available in Stone et al. (1983).

The following sections review the purpose and objectives of the meteorological investigation for characterizing the Hanford Site for a geologic repository, the rationale for developing such an investigation, the data gathering tasks required to supplement existing data and analyses, and the application of the results of these tasks.

8.3.1.5.5.1 Purpose and objectives

The specific purposes for investigating site meteorology for repository site characterization include the following:

- To provide information to address the issues, parameters, and goals identified in Section 8.2.
- To provide information on meteorological averages and extremes for the design of facilities and the scheduling of operations.
- To provide information to be used in site characterization studies that require meteorological data, especially studies of site groundwater (see Section 8.3.1.3.4.3.2) and surface water hydrology (see Section 8.3.1.3.3.1).
- To identify and characterize the frequency and intensity of meteorological conditions that may affect repository operation.
- To satisfy requirements of the DOE in 10 CFR 960 (DOE, 1987), the NRC in 10 CFR 60 (NRC, 1987), and the EPA in 40 CFR 191 (EPA, 1986).

Specific information gathering objectives for the investigation include data on the following:

- Winds.
 - Prevailing direction and average speed near the proposed repository location.
 - Frequency distribution of direction and speed as a function of season, time of day, and height above ground.
 - The spatial variation of near surface winds.

- Analysis of extreme winds.
- Several years of data of hourly average wind directions and speeds from several monitoring locations.
- Temperature.
 - Annual and monthly averages and extremes.
 - Hourly average values.
 - Spatial and vertical variation.
- Precipitation.
 - Annual average for rain and snow.
 - Seasonal variations.
 - Spatial variations.
 - Precipitation intensities.
 - Snow accumulation.
- Solar radiation.
 - Annual and monthly averages and extremes.
 - Daily and hourly maximum potential values.
 - Hourly average values.
- Atmospheric moisture (dew point temperature and relative humidity--annual and monthly averages and extremes).
- Atmospheric pressure (annual and monthly averages and extremes).
- Atmospheric mixing.
 - Annual and monthly averages of mixing height.
 - Several years of hourly values of mixing height.
 - Hourly values of atmospheric stability.

- Severe weather.
 - Hurricanes.
 - Tornadoes.
 - Severe winter storms (e.g., blizzards).
 - Dust storms.
 - Thunderstorms (including lightning strikes).
 - Air stagnation events.

8.3.1.5.5.2 Rationale

The regulatory basis for a meteorology investigation to characterize the Hanford Site are discussed in this section. Meteorology, atmospheric dispersion, and related information are required to address four of the issues identified in Section 8.2, which in turn are derived from the requirements of 10 CFR 960 (DOE, 1987), 10 CFR 60 (NRC, 1987), and 40 CFR 191 (EPA, 1986). These issues focus on radiological safety.

The issues for which meteorological information is required in order to reach a higher level finding are given below (DOE, 1986):

- Issue 2.1: During repository operation, closure, and decommissioning (a) will the expected average radiation dose received by members of the public within any highly populated area be less than a small fraction of the allowable limits and (b) will the expected radiation dose received by any member of the public in an unrestricted area be less than the allowable limits as required by 10 CFR 60.111, 40 CFR 191 Part A, and 10 CFR Part 20?
- Issue 2.2: Can the repository be designed, constructed, operated, closed, and decommissioned in a manner that ensures the radiological safety of workers under normal operations as required by 10 CFR 60.111 and CFR Part 20?
- Issue 2.3: Can the repository be designed, constructed, operated, closed, and decommissioned in such a way that credible accidents do not result in projected radiological exposures of the general public at the nearest boundary of the unrestricted area, or workers in the restricted areas, in excess of applicable limiting values?
- Issue 2.5: Can the higher level findings required by 10 CFR Part 960 be made for the qualifying conditions of the preclosure system guideline and the disqualifying and qualifying conditions of the technical guidelines for population density and distribution, site ownership and control, meteorology, and offsite installation and operations?

The specific sections of the 10 CFR 960 (DOE, 1987), 10 CFR 60 (NRC, 1987), and 40 CFR 191 (EPA, 1986) that relate to meteorologic issues are summarized below.

The 10 CFR 960 guidelines list three qualifying conditions (one favorable condition and two potentially adverse conditions) related to site meteorology and atmospheric dispersion. The conditions that pertain to atmospheric dispersion are stated in the guidelines stated below.

10 CFR 960.5-1 System Guidelines.

(a) *Qualifying Conditions--(1) Preclosure Radiological Safety.* Any projected radiological exposures of the general public and any projected releases of radioactive materials to restricted and unrestricted areas during repository operation and closure shall meet the applicable safety requirements set forth in 10 CFR Part 20, 10 CFR Part 60, and 40 CFR 191, Subpart A...

10 CFR 960.5-2-1 Population Density and Distribution.

(a) *Qualifying Condition.* The site shall be located such that, during repository operation and closure, (1) the expected average radiation dose to members of the public within any highly populated area will not be likely to exceed a small fraction of the limits allowable under the requirements specified in 960.5-1(a)(1), and (2) the expected radiation dose to any member of the public in an unrestricted area will not be likely to exceed the limit allowable under the requirements specified in 960.5-1(a)(1).

10 CFR 960.5-2-3 Meteorology.

(a) *Qualifying Condition.* The site shall be located such that expected meteorological conditions during repository operation and closure will not be likely to lead to radionuclide releases to an unrestricted area greater than those allowable under the requirements specified in 960.5-1(a)(1).

(b) *Favorable Condition.* Prevailing meteorological conditions such that any radioactive releases to the atmosphere during repository operation and closure would be effectively dispersed, thereby reducing significantly the likelihood of unacceptable exposures to any member of the public in the vicinity of the repository.

(c) *Potentially Adverse Conditions.* (1) Prevailing meteorological conditions such that radioactive emissions from repository operation or closure could be preferentially transported toward the localities in the vicinity of the repository with higher population densities than are the average for the region.

To address the issues posed by these potential conditions, meteorological data are required to properly estimate atmospheric dispersion. Sufficient data must be collected to characterize atmospheric transport from the proposed repository location to populated areas; corresponding data to characterize atmospheric diffusion must also be available. To numerically simulate radioactive releases, the use of an appropriate atmospheric dispersion model is required. Atmospheric dispersion experiments would provide data to select an appropriate model and to fine tune the model to adequately simulate the interactions between wind fields and the area's complex terrain.

The second potentially adverse condition presented in 10 CFR 960.5-2-3(c)(2) focuses on extreme weather events. This condition is stated as follows:

(2) History of extreme weather phenomena--such as hurricanes, tornadoes, severe floods, or severe and frequent winter storms--that could significantly affect repository operation or closure.

To address this condition, existing studies on extreme weather phenomena must be reviewed and additional analyses conducted if the existing studies are inadequate. Because many years of meteorological measurements and observations are required to record a large enough number of extreme weather events to adequately characterize the event's frequency and intensity, the existence of a lengthy meteorological data base for the Hanford Site should contribute greatly to resolving issues related to this potential condition.

The 10 CFR 60 lists several licensing criteria that must be addressed. Section 10 CFR 60.21 states that the safety analysis report must include "...An analysis of the...meteorology of the site." The analysis is "...to determine the degree to which each of the favorable and potentially adverse conditions, if present, has been characterized, and the extent to which it contributes to or detracts from isolation." Although this particular analysis would be conducted during the preparation of the safety analysis report, site characterization activities must provide sufficient data to address this concern.

Section 10 CFR 60.111 states that the "...geologic repository operations area shall be designed so that until permanent closure has been completed, radiation exposures and radiation levels...will at all times be maintained within the limits specified in Part 20 of this chapter and such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency." To determine if standards would be maintained, data on atmospheric transport and diffusion are required to support the necessary modeling efforts. These data and modeling efforts are also required to comply with 10 CFR 60.112, which calls for the siting and design of the repository and barriers "...to assure that releases of radioactive materials to the environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency with respect to both anticipated processes and events and unanticipated processes and events."

Section 10 CFR 60.122(c)(1) calls for knowledge of "Potential for flooding..." at the repository site. Studies must consider floods that could result from intense precipitation or rapid snow melt; site specific meteorological data would be required for this task.

Section 10 CFR 60.131 discusses design criteria for the repository to limit radiologic releases to the atmosphere and radiologic exposure. It calls for the design of facilities so that "...natural phenomena and environmental conditions anticipated at the [repository] will not interfere with necessary safety functions." This would require knowledge of the frequency and intensity of severe weather phenomena and estimates of the probability that certain values of key meteorologic parameters would be exceeded during any given year.

The 40 CFR 191, Subpart A, sets environmental standards for the proposed repository. Section 40 CFR 191.03 states that the "...Discharges of radioactive material and direct radiation from such management and storage and (2) all operations covered by Part 190 shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other critical organ." Once again, the estimation of dose requires the use of an appropriate dispersion model and the proper characterization of atmospheric dispersion parameters. Because this requirement calls for the consideration of all operations at the Hanford Site, atmospheric transport and diffusion from all potential emitters of radiologic material on the Hanford Site must be characterized, not just emissions from the proposed repository location.

The relationship between results of site meteorologic analyses accomplished under the climate investigation and the repository performance assessment is shown by Table 8.3.1.5-11. This table includes a list of supporting parameters from the site meteorologic analyses with corresponding performance parameters and performance measures. The performance measures and related performance parameters are derived directly from the issue resolution strategy described in Section 8.2.2. The supporting parameters are given expected values along with current confidence in the expected values. The final table entry is needed confidence in the value of the supporting parameter expected to be necessary to adequately determine the performance parameter.

8.3.1.5.5.3 Description of site meteorology study

Because an intense program of meteorologic monitoring and analysis has been conducted at the Hanford Site for over 40 yr, sufficient data and studies already exist to adequately address many of the meteorologic and atmospheric dispersion issues associated with the site characterization. Studies planned to address the meteorologic needs of other projects will provide even more information.

Table 8.3.1.5-11. Supporting parameter table for the meteorologic elements on radiologic safety issues (Issues 2.1, 2.2 and 2.3) (sheet 1 of 2)

System element; performance measure	Issue	Performance parameter	Supporting parameter	Test or analysis basis		
				Expected values ^a	Current confidence ^b	Needed confidence ^b
Airborne radionuclide concentrations	2.1, 2.2, 2.3	Wind speeds	Near-surface wind speed near exploratory shaft location	See Chapter 5	Medium	High
			Near-surface wind speeds at other monitoring locations	See Chapter 5	Medium	High
			Vertical variation in wind speed	See Chapter 5	Medium	High
	2.1, 2.2, 2.3	Wind direction	Near-surface wind direction near exploratory shaft location	See Chapter 5	Medium	High
			Near-surface wind direction at other monitoring locations	See Chapter 5	Medium	High
			Vertical variation in wind direction	See Chapter 5	Medium	High
	2.1, 2.2, 2.3	Atmospheric stability	Atmospheric stability near exploratory shaft location	See Chapter 5	Medium	High
			Spatial variation	See Chapter 5	Medium	High
			Mixing height	0 to 5,000 m,	Low	Medium
	2.1, 2.2, 2.3	Air temperature	Air temperature near exploratory shaft location	-3.25 to 46.1 °C	Medium	High
			Spatial variation in air temperature	-45 to 50 °C	Medium	High
			Relative humidity	5% to 100%	Medium	Medium
	2.1, 2.2, 2.3	Precipitation	Spatial variation in relative humidity	5% to 100%	Low	Medium
			Precipitation near exploratory shaft location	7.6% to 29.1 cm/yr	Medium	Medium
			Spatial variation in precipitation	4% to 100 cm/yr	Low	Medium
	2.2, 2.3	Surface air pressure	Surface air pressure	975% to 11,255 mb	High	Medium

PST88-2014-8.3.1.5-6

Table 8.3.1.5-11. Supporting parameter table for the meteorologic elements on radiologic safety issues (Issues 2.1, 2.2 and 2.3) (sheet 2 of 2)

System element; performance measure	Issue	Performance parameter	Supporting parameter	Test or analysis basis		
				Expected values ^a	Current confidence ^b	Needed confidence ^b
Severe weather	2.3	Tornadoes	Frequency of tornadoes	See Chapter 5	Low	Medium
			Intensity of tornadoes	See Chapter 5	Low	Medium
	2.3	Wind storms	Wind storms	See Chapter 5	Medium	Medium
	2.3	Lightning	Frequency of cloud-to-ground lightning strikes	See Chapter 5	Medium	Medium
	2.3	Duststorm	Frequency of duststorms	See Chapter 5	Medium	Medium
			Intensity of duststorms	See Chapter 5	Medium	Medium

^aExpected values are the range of values that have been measured in the past and should represent bounding values for the preclosure period.

^bHigh = >90%, Medium = >50%, Low = <50%.

PST88-2014-8.3.1.5-6

8.3.1.5.5.3.1 Study Component F: Site Meteorology

To fill in the information gaps, eight analyses, which together make up a single study, are being planned (Table 8.3.1.5-12). The first six focus on meteorologic and atmospheric dispersion questions; the final two would provide data for hydrologic studies.

8.3.1.5.5.3.1.1 Analysis F1--Comparison of Hanford Meteorology Station data with site meteorologic data.

Much of the data being used to represent the meteorologic conditions of the proposed repository location have been collected at the Hanford Meteorology Station. Although the station is located within the controlled area study zone, it is several kilometers (miles) from the proposed repository location; the question therefore arises as to just how applicable the data from the station are to the proposed repository location. It has been assumed that there is little significant spatial variation in meteorological parameters between the two sites. This assumption is based on the close proximity of the sites, their similar elevations, and lack of significant complex terrain between or near their locations. A preliminary comparison of wind data collected near ground level at the two locations supports this assumption; the joint frequency distributions of wind direction and wind speed from the two locations are very similar. It is assumed that this relationship holds for other meteorological parameters (e.g., precipitation and humidity) as well.

The first stage for this analysis would be to examine the existing wind and temperature data collected at the repository location and compare them to the data collected at the Hanford Meteorology Station. The second stage would be to deploy instruments to monitor precipitation, solar radiation, and atmospheric moisture at the proposed repository location. These instruments would be located on or near the existing 9.1-m (30-ft) tower at the proposed repository location. After these instruments have collected sufficient data for analysis, the next task would be to compare the new data from this location with data collected at the Hanford Meteorology Station. The degree of spatial variation for each parameter would be determined and a judgment made as to the general representativeness of data from the Hanford Meteorology Station to the proposed repository location.

8.3.1.5.5.3.1.2 Analysis F2--Monitoring of wind in the Cold Creek Valley area. In order to characterize atmospheric transport toward the west and northwest of the proposed repository location, wind monitoring equipment will be required in the Cold Creek Valley and surrounding hills. The existing Hanford Site network of over 20 wind monitoring stations does not adequately monitor conditions in this region. Most of these monitoring locations are concentrated in the region to the east through the south-southeast of the proposed repository location.

Table 8.3.1.5-12. Site meteorological analyses procedures

Analysis number	Analysis	Procedure
F1	Comparison of Hanford Meteorology Station data with site meteorologic data	Examine existing data. Deploy additional monitoring equipment. Analyze and compare data from the two sites
F2	Monitoring of wind in the Cold Creek Valley area	Examine layout of area and select locations for new wind monitoring stations. Analyze data and incorporate in characterization of atmospheric dispersion
F3	Assessment of wind data from temporary monitoring station	Process data from temporary stations. Determine wind characteristics at each site. Incorporate results in characterization of atmospheric dispersion
F4	Assessment of extreme meteorologic events	Review existing analyses. Upgrade analyses where appropriate and publish results
F5	Tracer testing of atmospheric dispersion from the proposed repository	Test equipment and procedures. Conduct preliminary experiments, analyze data, and modify experimental design. Conduct major set of experiments and analyze results
F6	Modeling of atmospheric dispersion	Select candidate models and conduct simulations. Identify worst-case scenarios
F7	Characterization of spatial variation in precipitation	Gather existing data and obtain a preliminary characterization. Identify sites for which additional data are required and deploy instrumentation. Evaluate past method for collecting precipitation
F8	Characterization of spatial variation of atmospheric moisture	Identify existing sources of data. Determine sites for which additional data are required. Collect and analyze new data

PST88-2014-8.3.1.5-7

The sites for existing monitoring equipment were selected in part on the basis of the location of population centers near the Hanford Site and the atmospheric transport from Hanford Site facilities into particular areas. Because of the lack of a significant population center in the near vicinity of the site's western boundary and the relative infrequency to transport in this direction, only three monitoring locations are located to the west through northwest of the proposed repository location. In order to more accurately estimate transport pathways and diffusion characteristics when winds do blow into this region, additional monitoring stations are required in the Cold Creek Valley area and neighboring hills.

For the first stage of this analysis, researchers would examine the layout of the Cold Creek Valley and other potential transportation corridors to the west and northwest of the proposed repository location. Appropriate sites for the deployment of additional wind-monitoring stations would be identified. Data to be collected at these stations would include wind direction, wind speed, and temperature. Data on precipitation (see Analysis F7) and atmospheric moisture (see Analysis F8) might also be collected at these sites. The next stage would be to analyze the new data. An evaluation would be made as to whether the new monitoring locations were providing useful information. Based on this analysis, some of the new stations might be moved to different locations while others might be removed

entirely. Additional stations might also be required. The final network of new stations would operate for a number of years; data from these stations would be combined with data from the existing monitoring network for use in characterizing and modeling atmospheric dispersion.

8.3.1.5.5.3.1.3 Analysis F3--Assessment of wind data from temporary monitoring stations. In addition to the meteorologic monitoring at the Hanford Meteorology Station and the 23 other wind and temperature-monitoring locations deployed through the area, there are several temporary 9.1-m (30-ft) meteorologic towers deployed at various locations to examine the local wind regime. Although data have been collected at several locations, data from these stations have not been analyzed in detail. Analyses of these data might reveal some new information on atmospheric transport patterns and local wind flows at critical locations.

The first stage for this analysis would be to process the data from temporary stations (including the performance of basic quality assurance checks). The next stage would be to analyze the data, determining the wind regimes at each site. Wind data would be examined as a function of season, time of day, and atmospheric stability. The third stage would be to compare data from the temporary stations with corresponding data from neighboring stations that are part of the permanent monitoring network. The final stage would be to incorporate results of these analyses into the atmospheric dispersion models to be used to estimate environmental impacts.

8.3.1.5.5.3.1.4 Analysis F4--Assessment of extreme meteorologic events. The proposed repository should be constructed in an area that is not characterized by frequent and intense extreme meteorological events. Such events include tornadoes, hurricanes, high winds, dust storms, heavy precipitation (both rain and snow), ice storms, lightning, and hail storms. If these events are unexpected and unprepared for, they could have devastating impacts on repository operations and safety. For example, the high winds, pressure gradients, and blowing debris associated with severe tornadoes can destroy or damage buildings, transportation vehicles, and heavy equipment. Lives can be lost and the integrity of some safety systems jeopardized. Heavy rains associated with severe storms can flood underground facilities. In the winter, snow loads could unduly stress building roof supports. Blizzards can shut down local and regional transportation routes, forcing a halt to operations and stranding workers.

Research has already been performed to document the frequency of occurrence and intensity of some severe weather events (e.g., tornadoes are addressed in Ramsdell and Andrews (1986)). In some cases, published research has involved the analysis of a limited meteorological data base that is much smaller than the data base currently available. For other events, a detailed analysis of the existing data has never been conducted. Therefore, the first stage of this analysis would involve the review of existing analyses of extreme meteorological events and a determination of the adequacy of each analysis. New analyses would be performed for events determined to be inadequately characterized.

The second stage of this analysis would involve conducting analyses of severe weather events for which no previous analyses exist and upgrading analyses that do not adequately determine the frequency and intensity of the event under consideration. Available data would be analyzed and updated where appropriate, and the results of new studies would be published.

8.3.1.5.5.3.1.5 Analysis F5--Tracer testing of atmospheric dispersion from the proposed repository. Although the network of wind-monitoring stations provides an excellent indication of atmospheric transport near the surface, it does not provide information about transport at higher elevations, interactions between the winds at different elevations, vertical velocities, or splitting of the flow near complex terrain features. To determine the accuracy of the models to be used to simulate atmospheric transport and diffusion processes, some direct monitoring of atmospheric dispersion is required. Measurements of atmospheric dispersion would then be used to modify these models to upgrade their performance for the Hanford Site.

Dispersion can be monitored through the use of an atmospheric tracer. Such tracers are gases or particles with properties that allow them to be detected in exceedingly small concentrations. One class of gaseous tracers are perfluorocarbon compounds. Some perfluorocarbon compounds have almost nonexistent background concentrations; therefore, very small quantities of these tracers are required for detection. Thus, comparatively small quantities need to be released. Because several different perfluorocarbon compounds make good tracers, multiple releases using different compounds can be conducted during a single experiment. A relatively simple, automated system exists for the ground sampling of perfluorocarbons.

Tracer testing would involve releases from the proposed repository location under a variety of meteorological conditions. Tracer releases under conditions in which atmospheric transport would be toward the southeast and east would allow an examination of the interactions between the wind field and the complex terrain on the east side of the Columbia River. Transport to the west and northwest would provide information about dispersion within the Cold Creek Valley or up the Columbia River.

The first stage for this analysis would be to test equipment, tracer release procedures, sampler setup procedures, and laboratory processes. The next stage would involve conducting preliminary experiments to examine ground level concentrations of a released tracer along the Hanford Site fenceline. In these experiments, a single array of samplers would be installed on the Columbia River border of the Hanford Site along the most common atmospheric transport route for releases from the repository site.

The third stage would be to analyze the data collected from the preliminary experiments. Based on the results of these experiments, modifications would be made to the experiment design for the main set of experiments.

The fourth stage would be the major set of the dispersion experiments. Sampling instrumentation would be set up in multiple arcs. The first arc

might be set up within the Hanford Site, the second arc might be along the site boundary, and the third arc might correspond to populated areas further downwind, such as arc from Kennewick, through Pasco, or Eltopia, Washington. Sampling arcs would be moved to the west or northwest for tracer releases when atmospheric transport would carry material in those directions.

The final stage would be to analyze the data collected in the main series of experiments. Based on the results of these analyses, atmospheric dispersion models can be tested and refined to provide the best simulation of atmospheric dispersion using typically available data.

8.3.1.5.5.3.1.6 Analysis F6--Modeling of atmospheric dispersion. The simulation of atmospheric dispersion from the proposed repository location is required to accurately estimate the radiological exposures that would result from routine releases to the atmosphere or accidental releases. Emphasis would be placed on identifying any scenarios that produced radiological exposures that violated the established guidelines.

The first stage for this analysis would be to select candidate atmospheric dispersion models for test runs to determine which, if any, is best suited to modeling atmospheric dispersion from the proposed repository location. The second stage would be to conduct a long-term simulation of releases from the proposed repository location to determine the prevailing transport pathways and the areas that could be most severely impacted by atmospheric releases. The third stage would be to identify the worst-case scenarios for atmospheric releases. A careful examination would be conducted to determine if any of the dose limits presented in the issues focusing on radiological impact would be violated.

8.3.1.5.5.3.1.7 Analysis F7--Characterization of spatial variation in precipitation. The existing network of precipitation samplers needs to be expanded to characterize the spatial variation of precipitation in the Pasco Basin. Since the establishment of the Hanford Meteorology Station, the liquid water content of precipitation (rainfall and melted snow and ice) has been measured on an hourly basis. In addition, separate measurements of hourly snowfall are made. In recent years, measurements of the total liquid water content of precipitation have been made at a number of monitoring locations on the Arid Land Ecology reservation that occupies the southwestern portion of the Hanford Site. Data from this network of precipitation samplers are stored at the Hanford Meteorology Station but have undergone only limited analysis. Additional precipitation monitoring has been performed by a number of researchers at several locations on the site. Sampling was conducted for limited periods of time to provide information for hydrological and biological studies.

Previous limited studies indicate that precipitation amounts show a significant variation with elevation in the western portion of the Hanford Site. Understanding the spatial variation in precipitation is important for computing groundwater recharge and for determining the total amount of precipitation falling into a valley from which flood waters may flow.

The first stage for this analysis would be to gather existing data on precipitation at the Hanford Meteorology Station and other monitoring locations. The data would then be examined to obtain a preliminary characterization of the spatial variation of precipitation across the Hanford Site; data not meeting minimum quality assurance standards would not be analyzed. Locations would be identified at which additional monitors need to be deployed.

The second stage would be to install monitoring equipment at the sites identified for additional monitoring. In particular, the Cold Creek Valley and surrounding slopes are of key interest to hydrologists. Some precipitation data are currently available from this region, but they are insufficient to characterize local precipitation in the detail that is required.

The third stage would be to analyze the data as available and to provide raw data to project hydrologists.

The final stage would involve evaluating past methods of collecting precipitation data to determine the adequacy of these methods. Experiments would be conducted in which gages with wind shields and superior collection surfaces would be operated in the vicinity of older precipitation collection devices. The data from different sets of instruments would be compared and researchers would try to determine if there are systematic differences between the values recorded by the instruments and how these differences vary as a function of certain meteorological conditions (e.g., wind speed and temperature). The characterization of systematic differences between different types of monitoring instruments would allow a postprocessing of existing data to resolve discrepancies caused by the instrumentation.

8.3.1.5.5.3.1.8 Analysis F8--Characterization of spatial variation of atmospheric moisture. Evaporation and evapotranspiration rates are important parameters for calculating groundwater recharge rates. The estimation of evaporation rates requires data on solar insolation, relative humidity, temperature, wind speed, and other parameters. For estimating evapotranspiration rates, additional information is required on soil characteristics, vegetation type and density, and other parameters. Of the meteorological parameters needed for estimating these rates on the Hanford Site, the least is known about the atmospheric moisture.

Atmospheric moisture can vary greatly over a short distance due to the presence of surface water, irrigation activities, or changes in vegetation. Relative humidity is routinely monitored at the Hanford Meteorology Station and more recently at sites established for hydrologic research. To better understand the spatial variation of relative humidity in key areas where hydrologists need to complete groundwater recharge, additional monitors will have to be deployed to measure atmospheric moisture.

The first stage for this analysis would be to identify existing sources of data on atmospheric moisture. The second stage would be to consult with hydrologists and determine the sites for which additional data are required

and then arrange for the deployment of additional monitors at these locations. Consideration will be given to colocating monitors at sites where wind, precipitation, and other meteorological data are also required. The final stage would involve the collection and analysis of data. Once data are collected and appropriate quality assurance checks have been completed, the data would be made available to hydrologic researchers.

8.3.1.5.5.4 Application of results

Results of the proposed data-gathering tasks will be used to increase knowledge of the meteorology of the site and characteristic atmospheric dispersion. This knowledge will be used to address the issue focusing on severe weather events and the issues focusing on radiological exposures to workers and the public.

Data on certain meteorological parameters will be directly provided to hydrologists for studies of surface and groundwater. In particular, these data would be used to estimate groundwater recharge rates. Data summarizing the available observations would provide input to the past climate and future climate studies to satisfy needs for modern climate data bases.

Information on site meteorology and atmospheric dispersion will be used for site selection, facility design, construction and operations scheduling, routine environmental monitoring, and emergency response applications.

8.3.1.5.5.5 Schedules and milestones for investigation

Figure 8.3.1.5-8 shows the schedules and selected milestones for this investigation. Work on the analyses supporting this investigation will begin early in the first year of study with initial planning sessions and field work to set up instrument packages. The early focus will be on the analyses that examine the representativeness of existing meteorological data for the proposed repository location (Analysis F1), monitor the winds of the Cold Creek Valley (Analysis F2), and obtain additional information for characterizing the spatial variation of precipitation (Analysis F7) and moisture (Analysis F8). For analyses involving data collection, a minimum of 2 yr of new data will be collected before final analyses are conducted. Work on the remaining analyses (Analysis F3 through F6) will begin in the middle portion of the first year of study. Analysis of extreme meteorological events (Analysis F4) and wind data from temporary monitoring stations (Analysis F3) would be completed early in the third year of study. Field work for the atmospheric tracer testing analysis (Analysis F5) would be conducted late in the first year of study and continue through the next year. Results of these analyses would be available by the third or fourth year of study. Preliminary modeling work (Analysis F6) would be conducted simultaneously with the other analyses, particularly the tracer testing analysis. Final modeling would be conducted after the completion of the tracer testing analysis and completed by the end of site characterization.

ACTIVITY	TIME									
SITE METEOROLOGY								▽ ¹	▽ ²	

- ▽¹ CHARACTERISTICS AND SPATIAL VARIATION OF PRECIPITATION PROVIDED TO THE SURFACE WATER SYSTEM STUDY.
 ▽² COMPLETE SITE METEOROLOGY INVESTIGATION

PSM 2014-8.3.1.5-1

Figure 8.3.1.5-8. Schedule and selected milestones of the site meteorology investigation.

8.3.1.5.6 References

- Ahlbrandt, T. S., 1983. "Aolian Sediments and Processes," in Developments in Sedimentology, M. E. Brookfield and T. S. Ahlbrandt (eds.), Elsevier Publishing, New York, New York, 660 pp. [MF 4851]
- Andrews, J. T., and M. A. W. Mahaffy, 1976. "Growth Rate of the Laurentide Ice Sheet and Sea Level Lowering (with emphasis on the 115,000 bp sea level low)," Quaternary Research, Vol. 6, pp. 167-183. [MF 1208]
- Arigo, R., S. E., Howe, and T. Webb, III, 1984. Climate Calibration of Pollen Data: A User's Guide for the Applicable Computer Programs in the Statistical Package for Social Sciences (SPSS), NUREG/CR-3847, U.S. Nuclear Regulatory Commission, Washington, D.C., 36 pp. [MF 4578]
- Baker, R. G., 1983. "Holocene Vegetational History of the Western United States," The Holocene, H. E. Wright, Jr. (ed.), University Minnesota Press, Minneapolis, Minnesota, pp. 109-127. [MF 1220]
- Baker, V. R., 1973. "Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington," Geological Society of America Special Paper, Vol. 144, pp. 4 and 21. [MF 0028]
- Baker, V. R., and R. C. Bunker, 1985. "Cataclysmic Late Pleistocene Flooding from Glacial Lake Missoula: A Review," Quaternary Science Reviews, Vol. 4, pp. 1-41. [MF 3123]
- Barnett, T. P., 1981. "Statistical Prediction of North American Air Temperatures from Pacific Predictors," Monthly Weather Review, Vol. 109, pp. 1021-1041. [MF 4579]
- Barnosky, C. W., 1985. "Late Quaternary Vegetation from the Southwestern Columbia Basin, Washington," Quaternary Research, Vol. 23, pp. 109-122. [MF 1227]
- Bartlein, P. J., and T. Webb, 1985. "Mean July Temperature at 6,000 yr bp in Eastern North America: Regression Equations for Estimates from Fossil-Pollen Data. Syllageus 55 (Climate Change in Canada 5; Critical Periods in the Quaternary Climatic History of Northern North America)," Natural Museums of Canada, C. R. Harrington (ed.), National Museum of Natural Sciences, Ottawa, pp. 301-344. [MF 1233]
- Bartlein, P. J., T. Webb, and E. C. Fleri, 1984. "Holocene Climatic Change in the Northern Midwest: Pollen-Derived Estimates," Quaternary Research, Vol. 22, pp. 361-374. [MF 1234]
- Berger, A. L., 1978a. "Long-Term Variations of Caloric Insolation Resulting from Earth's Orbital Elements," Quaternary Research, Vol. 9, pp. 139-167. [MF 0705]

- Berger, A. L., 1978b. "Contribution n° 18 Mai 1978: A Simple Algorithm to Compute Long Term Variations of Daily or Monthly Insolation," Institut d'Astronomie et de Geophysique, Universite' Catholique de Louvain, Appendix 1979, Apendix B, 1979. [MF 3035]
- Birks, H. J. B., 1981. "The Use of Pollen Analysis in the Reconstruction of Past Climates: A Review," Climate and History, T. M. L. Wigley, et al. (eds.), Cambridge University Press, pp. 111-138. [MF 1242]
- Birks, H. J. B., and H. H. Birks, 1980. Quaternary Paleoecology, University Park Press, Baltimore, Maryland, pp. 183-187. [MF 1243]
- Blasing, T. J., and H. C. Fritts, 1976. "Reconstructing Past Climatic Anomalies in the North Pacific and Western North America from Tree-Ring Data," Quaternary Research, Vol. 6, pp. 563-580. [MF 1247]
- Bowen, D. Q., 1978. Quaternary Geology, Pergamon Press, New York, New York. [MF 1252]
- Budd, W. F., and J. N. Smith, 1981. "The Growth and Retreat of Ice Sheets in Response to Orbital Radiation Changes," Sea Level Ice and Climatic Change, I. Allison (ed.), International Association of Hydrological Sciences, Publication Number 131, pp. 369-409. [MF 1278]
- Budd, W. F., D. Jenssen, and U. Radok, 1971. Derived Physical Characteristics of the Antarctic Ice Sheet, Australian National Antarctic Research Expeditions (ANARE), Interim Reports, Series A (IV), Glaciology, Publication 120, Antarctic Division, Department of Supply, Melbourne, Australia. [MF 3510]
- Burden, R. L., and J. D. Faires, 1985. Numerical Analysis: Third Edition, Prindle, Weber & Schmidt Publishers, Boston, Massachusetts, pp. 586-589. [MF 4441]
- Clarke, G. K. C., W. H. Mathews, and R. T. Pack, 1984. "Outburst Floods from Glacial Lake Missoula," Quaternary Research, Vol. 22, pp. 289-299. [MF 1290]
- CLIMAP, 1976. "The Surface of the Ice-Age Earth," Science, Vol. 191, pp. 1131-1137. [MF 0169]
- CLIMAP, 1981. Seasonal Reconstructions of the Earth's Surface at the Last Glacial Maximum, Geological Society of America Map and Chart Series, MC-36, Boulder, Colorado. [MF 1295]
- Compton, R. R., 1962. Manual of Field Geology, John Wiley and Sons, Inc., New York, New York. [MF 4445]
- Craig, R. G., and J. P. Hanson, 1986. Erosion Potential from Missoula Floods in the Pasco Basin, Washington, PNL-5684, Pacific Northwest Laboratory, Richland, Washington. [MF 3166]

- Craig, R. G., and B. L. Roberts, 1984. "Seasonal Patterns of Precipitation and Temperature in the Southwest U.S. at the Time of the Last Glacial Maximum," American Quaternary Association, Eighth Biennial Meeting, Program and Abstracts, University of Illinois, Urbana, Illinois. [MF 3040]
- Craig, R. G., and M. P. Singer, 1984. "A Theoretical Study of Lake Missoula Jokulhlaups in the Late Pleistocene," Geological Society of America Abstracts with Programs, Vol. 16, No. 5, pp. 276-277. [MF 3009]
- Cropper, J. P., and H. C. Fritts, 1986. A 360 Year Temperature and Precipitation Record for the Pasco Basin Derived from Tree-Ring Data, DOE/RL/01830-T46, Pacific Northwest Laboratory, Richland, Washington. [MF 1310]
- Davis, M. B., 1967. "Pollen Deposition in Lakes as Measured by Sediment Traps," Geological Society of America Bulletin, Vol. 78, pp. 849-858. [MF 1317]
- Davis, M. B., L. B. Brubaker, and T. Webb, 1973. "Calibration of Absolute Pollen Influx," Quaternary Plant Ecology, H. J. B. Birks and R. G. West (eds.), Blackwell Scientific Publishers, Oxford, pp. 9-26. [MF 1318]
- Diaz, H. F., 1986. "An Analysis of Twentieth Century Climate Fluctuations in Northern North America," Journal of Climate and Applied Meteorology, Vol. 25, pp. 1625-1657. [MF 4852]
- DOE, 1986. Environmental Assessment, Reference Repository Location, Hanford Site, Washington, DOE/RW-0070, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C., p. 6-148. [MF 3175]
- DOE, 1987. General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories, Title 10, Code of Federal Regulations, Part 960, U.S. Department of Energy, Washington, D.C. [MF 4849]
- EPA, 1986*. Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, D.C. [MF 4906]
- Faegri, K., and J. Iversen, 1975. Textbook of Pollen Analysis, Hafner Publishing Company, New York, New York, 295 pp. [MF 1347]
- Fritts, H. C., 1976. Tree-Rings and Climate, Academic Press, New York, New York, 567 pp. [MF 1356]

*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Subpart B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

- Fritts, H. C., 1985. "Tree-Ring Analysis (Dendroclimatology)," The Encyclopedia of Climatology, J. E. Oliver (ed.), Hutchinson-Ross, Stroudsburg, Pennsylvania. [MF 1357]
- Gates, W. L., 1976. "Numerical Simulation of an Ice-Age Climate With a Global General Circulation Model," Journal of Atmospheric Science, Vol. 33, pp. 1844-1873. [MF 0717]
- Gillespie, R., F. A. Street-Perrott, and R. Switsur, 1983. "Post-Glacial Arid Episodes in Ethiopia Have Implications for Climate Prediction," Nature, Vol. 306, pp. 680-683. [MF 1368]
- Glen, J. W., 1955. "The Creep of Polycrystalline Ice," Proceedings of the Royal Society London, Series A, Vol. 228, pp. 519-538. [MF 1370]
- Grigoryan, S. S., M. S. Krass, and P. A. Shumskiy, 1976. "Mathematical Model of a Three-Dimensional Non-Isothermal Glacier," Journal of Glaciology, Vol. 17, pp. 401-417. [MF 1381]
- Hasselmann, K., 1976. "Stochastic Climate Models, Part I, Theory," Tellus, Vol. 28, pp. 473-484. [MF 1395]
- Hays, J. D., J. Imbrie, and N. J. Shackleton, 1976. "Variations in the Earth's Orbit: Pacemaker of the Ice Age," Science, Vol. 194, No. 4270, pp. 1121-1132, Copyright 1976 by the AAAS. [MF 1396]
- Heikkinen, O., 1984. "Dendrochronological Evidence of Variations of Coleman Glacier, Mount Baker, Washington, U.S.A.," Arctic and Alpine Research, Vol. 16, No. 1, pp. 53-64. [MF 1398]
- Heusser, C. J., 1957. "Variations of Blue, Hoh, and White Glaciers in Recent Centuries," Arctic, Vol. 10, pp. 139-150. [MF 1402]
- Heusser, C. J., 1978. "Modern Pollen Rain of Washington," Canadian Journal Botany, Vol. 56, pp. 1510-1517. [MF 1403]
- Heusser, C. J., 1983. "Vegetational History of the Northwestern United States Including Alaska," Late Quaternary Environments of the United States, The Late Pleistocene, Vol. 1, S. C. Porter (ed.), University of Minnesota Press, Minneapolis, Minnesota, pp. 239-258. [MF 1404]
- Heusser, C. J., L. E. Heusser, and S. S. Streeter, 1980. "Quaternary Temperatures and Precipitation for the North-West Coast of North America," Nature, Vol. 286, pp. 702-704. [MF 1405]
- Howe, S. E., and T. Webb, 1983. "Calibrating Pollen Data in Climatic Terms: Improving the Methods," Quaternary Science Reviews, Pergamon Press Ltd., Great Britain, Vol. 2, pp. 17-51. [MF 1414]
- Imbrie, J., and J. Z. Imbrie, 1980. "Modeling the Climatic Response to Orbital Variations," Science, Vol. 207, pp. 943-953. [MF 1421]

- Jenssen, D., 1977. "A Three-Dimensional Polar Ice-Sheet Model," Journal of Glaciology, Vol. 18, No. 80, pp. 373-389. [MF 1432]
- Karl, T. R., C. N. Williams, Jr., and P. J. Young, 1986. "A Model to Estimate the Time of Observation Bias Associated with Monthly Mean Maximum and Mean Temperatures for the United States," Journal of Climatology and Applied Meteorology, Vol. 25, pp. 145-160. [MF 4853]
- Kay, P. A., and J. T. Andrews, 1983. "Re-evaluation of Pollen-Climate Transfer Functions in Keewatin, Northern Canada," Annals Association American Geographers, Vol. 73, pp. 550-559. [MF 1435]
- Kerr, R. A., 1984. "Climate Since the Ice Began to Melt," Science, Vol. 226, No. 4672, pp. 326-327. [MF 1438]
- Klein, W. H., 1985. "Space and Time Variations in Specifying Monthly Mean Surface Temperature from the 700 mb Height Field," Monthly Weather Review, Vol. 113, pp. 227-290. [MF 4854]
- Kukla, G., A. Berger, R. Lotti, and J. Brown, 1981. "Orbital Signature of Interglacials," Nature, Vol. 290, pp. 295-300. [MF 1442]
- Kutzbach, J. E., and P. J. Guetter, 1984. "Sensitivity of Late-Glacial and Holocene Climates to the Combined Effects of Orbital Parameter Changes and Lower Boundary Condition Changes," Annals of Glaciology, Vol. 5, pp. 85-87. [MF 3019]
- Kutzbach, J. E., and H. E. Wright, Jr., 1985. "Simulations of the Climate of 18,000 Years B.P.: Results for the North American/North Atlantic/European Sector and Comparison with the Geologic Record of North America," Quaternary Science Reviews, Vol. 4, pp. 147-187. [MF 4606]
- Mack, R. N., and V. M. Bryant, Jr., 1974. "Modern Pollen Spectra from the Columbia Basin, Washington," Northwest Sciences, Vol. 48, No. 3, pp. 183-194. [MF 1467]
- Mahaffy, M. W., 1976. "A Three-Dimensional Numerical Model of Ice Sheets: Tests of the Barnes Ice Cap, Northwest Territories," Journal of Geophysical Research, Vol. 81, No. 6, pp. 1059-1066. [MF 1469]
- Manabe, S., and A. H. Broccoli, 1984. "The Influence of Continental Ice Sheets on the Climate of an Ice Age," Journal of Geophysical Research, Vol. 90, pp. 2167-2190. [MF 1470]
- Mathewes, R. W., and L. E. Heusser, 1981. "A 12,000 Year Palynological Record of Temperature and Precipitation Trends in Southwestern British Columbia," Canadian Journal Botany, Vol. 59, pp. 707-710. [MF 1472]
- McInnes, B., U. Radok, W. F. Budd, and I. N. Smith, 1985. On the Surging Potential of Polar Ice Streams, "Part 1, Sliding and Surging of Large Ice Masses--A Review," CIRES, 53 p. [MF 4609]

- Mehring, P. J., Jr., 1985. Late Quaternary Vegetation and Climates of South-Central Washington, Unpublished Report to Pacific Northwest Laboratory, Richland, Washington. [MF 1482]
- Mehring, P. J., Jr., and P. E. Wigand, 1986. "Western Juniper in the Holocene," Paper Presented at the Pinyon-Juniper Conference, Reno, Nevada, January 13-16, 11 pp. [MF 4855]
- Moore, T. C., Jr., 1973. "Late Pleistocene-Holocene Oceanographic Changes in the Northeastern Pacific," Quaternary Research, Vol. 3, pp. 99-109. [MF 1495]
- Moore, T. C., Jr., L. H. Burckle, K. Geitzenauer, B. Lutz, A. Molina-Cruz, J. H. Robertson, H. Sachs, C. Sancetta, J. Thiede, P. Thompson, and C. Wenkam, 1980. "The Reconstruction of Sea Surface Temperatures in the Pacific Ocean of 18,000 bo.," Marine Micropaleontology, Vol. 5, pp. 215-247. [MF 1496]
- Mullineaux, D. R., R. E. Wilson, W. F. Ebaugh, R. Fryxel, and M. Rueben, 1978. "Age of the Last Major Scabland Flood of the Columbia River Plateau in Eastern Washington," Quaternary Research, Vol. 10, pp. 171-180 [MF 2350]
- North, G. R., J. G. Mengel, and D. A. Short, 1983. "Simple Energy Balance Model Resolving the Seasons and the Continents: Application to the Astronomical Theory of the Ice Ages," Journal of Geophysical Research, Vol. 88, No. C11, pp. 6576-6586. [MF 4856]
- NRC, 1985. Standard Format and Content of Site Characterization Plans for High-Level-Waste Geologic Repositories, Draft Regulatory Guide 4.17, Proposed Revision 1 to Draft Regulatory Guide 4.17, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C., pp. 36-39. [MF 3556]
- NRC, 1987. Disposal of High-Level Radioactive Wastes in Geologic Repositories: Licensing Procedures, Title 10, Code of Federal Regulations, Part 60, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4903]
- Overpeck, J. T., T. Webb, and I. C. Prentice, 1985. "Quantitative Interpretation of Fossil Pollen Spectra: Dissimilarity Coefficients and the Method of Modern Analog," Quaternary Research, Vol. 23, pp. 87-108. [MF 1518]
- Paterson, W. S. B., 1981. "Glacier Flow I: Ice Deformation," The Physics of Glaciers, 2nd Edition, Pergamon Press, Inc., Elmsford, New York, pp. 83, 153-161. [MF 1522]
- Pielke, R. A., 1984. Mesoscale Meteorological Modeling, Academic Press Inc. [MF 4354]

- Pollard, D., 1984. "Some Ice Age Aspects of a Calving Ice Sheet," in Milankovitch and Climate Part II, A. L. Berger, J. Imbrie, J. Hayes, G. Kukla, B. Saltzman (eds.), D. Reidel Publishing, Dordrecht, Netherlands, pp. 541-546. [MF 1528]
- Porter, S. C., K. L. Pierce, and T. D. Hamilton, 1983. "Late Wisconsin Mountain Glaciation in the Western United States," The Late Pleistocene, University Minnesota Press, Minneapolis, Minnesota, Chapter 4, pp. 71-111. [MF 1532]
- Prentice, I. C., 1985. "Pollen Representation, Source Area, and Basin Size: Toward a Unified Theory of Pollen Analysis," Quaternary Research, Vol. 23, pp. 76-86. [MF 1536]
- Radok, U., R. G. Barry, D. Janssen, R. A. Keen, G. N. Kiladis, and B. J. McInnes, 1982. Climatic and Physical Characteristics of the Greenland Ice Sheet, Parts I and II, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado. [MF 3558]
- Ramsdell, J. V., and G. L. Andrews, 1986. Tornado Climatology of the Contiguous United States, NUREG/CR-4461, U.S. Nuclear Regulatory Commission, Washington, D.C., 292 pp. [MF 4857]
- Rogers, J. C., 1976. "Sea Surface Temperature Anomalies in the Eastern North Pacific and Associated Wintertime Atmospheric Fluctuations over North America, 1960-73," Monthly Weather Review, Vol. 104, No. 8, pp. 985-993. [MF 4617]
- Ruddiman, W. F., 1985. "Climate Studies in Ocean Cores," Paleoclimate Analysis and Modeling, A. D. Hecht (ed.), John Wiley and Sons, New York, New York, pp. 198, 203-209, 223. [MF 1554]
- Sachs, H. M., 1973. "Late Pleistocene History of the North Pacific: Evidence from a Quantitative Study of Radiolaria in Core V21-173," Quaternary Research, Vol. 3, pp. 89-98. [MF 1558]
- Saltzman, B. A., and A. Sutera, 1984. "A Model of the Internal Feedback System Involved in Late Quaternary Climatic Variation," Journal of Atmosphere Science, Vol. 41, No. 5, pp. 736-745. [MF 4858]
- Sarna-Wojcicki, A. M., D. E. Champion, and J. O. Davis, 1983. "Holocene Volcanism in the Conterminous United States and the Role of Silicic Volcanic Ash Layers in Correlation of Latest-Pleistocene and Holocene Deposits," Late-Quaternary Environments of the United States, The Holocene, H. E. Wright, Jr. (ed.), University Minnesota Press, Minneapolis, Minnesota, Vol. 2, Chapter 5, pp. 52-57. [MF 1564]
- Schlesinger, M. E., 1984. "Climate Model Simulation of CO₂ - Induced Climatic Change," Advanced in Geophysics, Vol. 26, pp. 141-235. [MF 4859]

- Schlesinger, M. E., 1986. "Equilibrium and Transient Climatic Warming Induced by Increased Atmospheric CO₂," Climate Dynamics, Vol. 1, pp. 35-51. [MF 4860]
- Sheaffer, J. D., and E. R. Reiter, 1985. "Influence of Pacific Sea Surface Temperatures on Seasonal Precipitation over the Western Plateau of the United States," Archives for Meteorology, Geophysics, and Bioclimatology, Ser. A34, pp. 111-130. [MF 4621]
- Sheppard, J. C., 1975. A Radiocarbon Dating Primer, Vol. 338, Washington State University College Engineering Bulletin, Pullman, Washington, p. 77. [MF 1576]
- Silling, S. A., 1983. Final Technical Position on Documentation of Computer Codes for High-Level Waste Management, NUREG-0856, Division of Waste Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, Washington, D.C., 12 pp. [MF 1049]
- Simmons, A. J., and L. Bengtsson, 1984. "Atmospheric General Circulation Models: Their Design and Use for Climate Studies," The Global Climate System, J. Houghton (ed.), Cambridge University Press, pp. 37-62. [MF 1577]
- Sims, J. D., 1975. "Determining Earthquake Recurrence Intervals from Deformational Structures in Young Lacustrine Sediments," Tectonophysics, Vol. 28, pp. 142-152. [MF 4861]
- Singer, M. P., and R. G. Craig, 1984. "Volume-Area-Depth Relations in the Lake Missoula Basin," Geological Society of America Abstracts with Programs 1984, Vol. 16, No. 5, p. 333. [MF 3027]
- Stone, W. A., J. M. Thorp, O. P. Gifford, and D. J. Hohnik, 1983. Climatological Summary for the Hanford Area, PNL-4622, Pacific Northwest Laboratory, Richland, Washington. [MF 0346]
- Waite, R. B., Jr., 1980. "About Forty Last-Glacial Lake Missoula Jopkulhlaups Through Southern Washington," Journal of Geology, Vol. 88, pp. 653-679. [MF 1035]
- Waite, R. B., Jr., and R. M. Thorson, 1983. "The Cordilleran Ice Sheet in Washington, Idaho, and Montana," The Late Pleistocene, S. C. Porter (ed.), University Minnesota Press, Minneapolis, Minnesota, Chapter 3, pp. 53-70. [MF 1634]
- Walsh, J. E., and M. B. Richman, 1981. "Seasonality in the Associations Between Surface Temperatures over the United States and the North Pacific Ocean," Monthly Weather Review, Vol. 109, pp. 767-783. [MF 4630]
- Wang, H. F., and M. P. Anderson, 1982. Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods, W. H. Freeman and Company, New York, New York, pp. 103-109. [MF 4444]

- Webb, T., III, 1985. A Global Paleoclimatic Data Base for 6000 yr B.P., TRO18, DOE/EV/10097-6, Carbon Dioxide Research Division, U.S. Department of Energy, Washington, D.C. [MF 4631]
- Webb, T., and D. R. Clark, 1977. "Calibrating Micropaleontological Data in Climatic Terms: A Critical Review," Annals New York Academic Sciences, Vol. 288, pp. 93-118. [MF 1641]
- Wendland, W. M. and R. A. Bryson, 1981. "Northern Hemisphere Airstream Regions," Monthly Weather Review, Vol. 109, pp. 255-270. [MF 4862]
- Williams, L. D., and T. M. L. Wigley, 1983. "A Comparison of Evidence for Late Holocene Summer Temperature Variations in the Northern Hemisphere," Quaternary Research, Vol. 20, pp. 286-307. [MF 0752]
- Winter, T. C., and H. E. Wright, Jr., 1977. "Paleohydrologic Phenomena Recorded by Lake Sediments," EOS, Vol. 58, pp. 188-196. [MF 1648]

9 2 1 2 5 5 0 3 3 0

SITE CHARACTERIZATION PLAN

Chapter 8 - SITE CHARACTERIZATION PROGRAM

Section 8.3.1.6

Specific Program for Natural Resource Potential

9 2 1 2 5 5 5 0 3 3 1

THIS PAGE
INTENTIONALLY
LEFT BLANK

9 2 1 2 5 5 5 0 3 3 2

TABLE OF CONTENTS

	<u>Page</u>
8.3.1.6 Specific program for natural resource potential	8.3.1.6-1
8.3.1.6.1 Purpose and objectives	8.3.1.6-6
8.3.1.6.2 Rationale	8.3.1.6-6
8.3.1.6.3 Investigation of mineral, hydrocarbon, and geothermal resource potential	8.3.1.6-10
8.3.1.6.3.1 Purpose and objectives	8.3.1.6-10
8.3.1.6.3.2 Rationale	8.3.1.6-11
8.3.1.6.3.3 Description of study	8.3.1.6-12
8.3.1.6.3.4 Application of results	8.3.1.6-27
8.3.1.6.3.5 Schedule and milestones	8.3.1.6-28
8.3.1.6.4 Investigation of water resource potential	8.3.1.6-28
8.3.1.6.4.1 Purpose and objectives	8.3.1.6-31
8.3.1.6.4.2 Rationale	8.3.1.6-31
8.3.1.6.4.3 Description of study	8.3.1.6-32
8.3.1.6.4.4 Application of results	8.3.1.6-35
8.3.1.6.4.5 Schedule and milestones	8.3.1.6-35
8.3.1.6.5 References	8.3.1.6-37

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.1.6-1	Location map	8.3.1.6-3
8.3.1.6-2	Breakdown of investigations	8.3.1.6-5
8.3.1.6-3	Borehole locations	8.3.1.6-17
8.3.1.6-4	Location map for Columbia Basin exploration wells . . .	8.3.1.6-21
8.3.1.6-5	Mineral, hydrocarbon, and geothermal resource potential investigation schedule	8.3.1.6-29
8.3.1.6-6	Organization of water resource potential study	8.3.1.6-33
8.3.1.6-7	Water resource potential investigation schedule	8.3.1.6-36

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.1.6-1	Parameters addressed by natural resource potential investigations	8.3.1.6-7
8.3.1.6-2	Tasks, tests, analyses for mineral, hydrocarbon, and geothermal natural resource potential study	8.3.1.6-13
8.3.1.6-3	Columbia Basin exploratory wells	8.3.1.6-20
8.3.1.6-4	Major milestones and expected delivery dates of mineral, hydrocarbon, and geothermal resource potential investigation	8.3.1.6-28
8.3.1.6-5	Factors influencing water resource development	8.3.1.6-34
8.3.1.6-6	Major milestones and expected delivery dates for water resource potential investigation	8.3.1.6-35

This page intentionally left blank.

9 2 1 2 5 5 5 0 3 3 6

8.3.1.6 Specific program for natural resource potential

This section presents site characterization plans for the evaluation of the resource potential at the Hanford Site. The natural resources that are considered in this section include hydrocarbon, geothermal, metallic and nonmetallic minerals, fuel minerals (coal, peat, and uranium), and water.

Background

Present information on mineral and hydrocarbon resource potential of the Pasco Basin and vicinity was summarized in Section 1.7. Section 8.3.1.6 is based on previous reports focused on resources that occur on the Columbia Plateau and in the vicinity of the Hanford Site. No resource evaluations have been made on the Hanford Site because it has been closed to all exploration activities since its establishment in the early 1940s. Prior to that time, natural gas, gold placers, sand and gravel deposits, and basalts for crushed rock products were known to occur on the site. Production records are not available. Mineral resources known to occur within the Columbia Plateau consist of low unit value minerals and rock products such as diatomaceous earth, pumice, sand and gravel, and quarry rock. Low-grade gold-bearing placer deposits along the modern Columbia River (Blalock Island) are the only known mineral deposits that have the potential for high unit value.

Gas was first discovered in eastern Washington State in 1913 on the northern flank of Rattlesnake Mountain, 19 km (12 mi) south of the controlled area study zone. The Rattlesnake gas field produced from 1929 until 1941, when production was ceased. The low-pressure, 16-well field apparently produced from a porous basalt reservoir that was sealed by an overlying clay layer. The source of the gas is unknown. A total volume of $37 \times 10^6 \text{ m}^3$ (1.3 BCF) of gas was produced. Analyses of the gas composition and BTU content from several wells in the field were presented in Section 1.7 (Table 1.7-3). The Rattlesnake gas field is discussed under the hydrocarbon resource component as a task in Section 8.3.1.6.3.3.

Renewed interest in exploration for oil and gas occurred in the early 1950s in the Columbia Plateau when several major oil and gas companies (Standard Oil Company of California, Shell, Texaco, Richfield, Union, Sohio) conducted geologic investigations. These activities led to oil and gas leases on several hundred thousand acres of land, with some major blocks adjacent to the Hanford Site, and the drilling of one deep exploratory well. This deep exploratory well (the Rattlesnake Hills Unit No. 1) was drilled by the Standard Oil Company of California to a total depth of 3,250 m (10,655 ft) on the Rattlesnake Hills anticline adjacent to the southeast corner of the Hanford Site. The well bottomed in Grande Ronde Basalt and recovered only minor shows of gas.

In the early 1980s, several deep oil and gas exploratory wells drilled in the Columbia Plateau near the Hanford Site penetrated the Columbia River basalt section and encountered significant, natural gas with distillate in the

sub-basalt sediments. The nearest of these exploratory wells (the Shell BN No. 1-9) is located on the Saddle Mountain anticline approximately 26 km (16 mi) north of the controlled area study zone. Drilling was completed in 1984 to a depth of 5,343 m (17,518 ft); gas with distillate was recovered at a depth of 3,660 m (12,000 ft) in the sub-basalt sediments. In August 1987, Shell spud the Darcell-Western No. 1 well approximately 32 km (20 mi) northeast of Pasco, Washington. These exploratory well results indicate there is a potential for major reserves of hydrocarbons in the Columbia Plateau.

The Cold Creek syncline (Fig. 8.3.1.6-1) is considered a less favorable location to explore for sub-basalt structural traps. However, this tentative conclusion must be evaluated further during site characterization, because it is based on the assumption that the structural configuration of the sub-basalt sedimentary rocks can be determined by the present structure of the overlying basalts.

Present information on geothermal resource potential has been summarized in Sections 1.7 and 1.3.2.5. Low-temperature geothermal waters (ranging from 25 to 50 °C) are present at depths as shallow as 915 m (3,000 ft) in the Pasco Basin and throughout the Columbia Plateau. With present technology, such water could be used directly (e.g., space heating or agricultural uses), but there is no recognized high-temperature potential for electrical generation. Temperature measurements and surveys run in the boreholes on the Hanford Site need to be assessed to determine if the geothermal resource potential is similar to that indicated for the Pasco Basin and Columbia Plateau.

Surface water and groundwater resources of the Pasco Basin and vicinity are discussed in Sections 3.3, 3.8, and 3.9.7. Water is used primarily for irrigation and industry, with a smaller percentage devoted to municipal and domestic purposes. Surface water currently supplies over 90% of the total water demand in the Pasco Basin. Groundwater withdrawals are significant in some areas (e.g., upper Cold Creek Valley). Demand for both surface water and groundwater is likely to increase in the future, and the projected magnitude of this increase must be evaluated as part of the site characterization.

Summary of program

Two resource potential investigations have been developed in order to fulfill parameter needs derived from the issue resolution strategies (see Section 8.2.1). The investigations will increase the present understanding of resource potential at the Hanford Site and will provide the basis for predicting future resource potential under varying socioeconomic conditions. Information from resource potential investigations is critical for an adequate determination of site performance relative to the regulatory requirements for potential for inadvertent human intrusion, groundwater travel time, and radionuclide release. Changes in radionuclide release may occur due to human

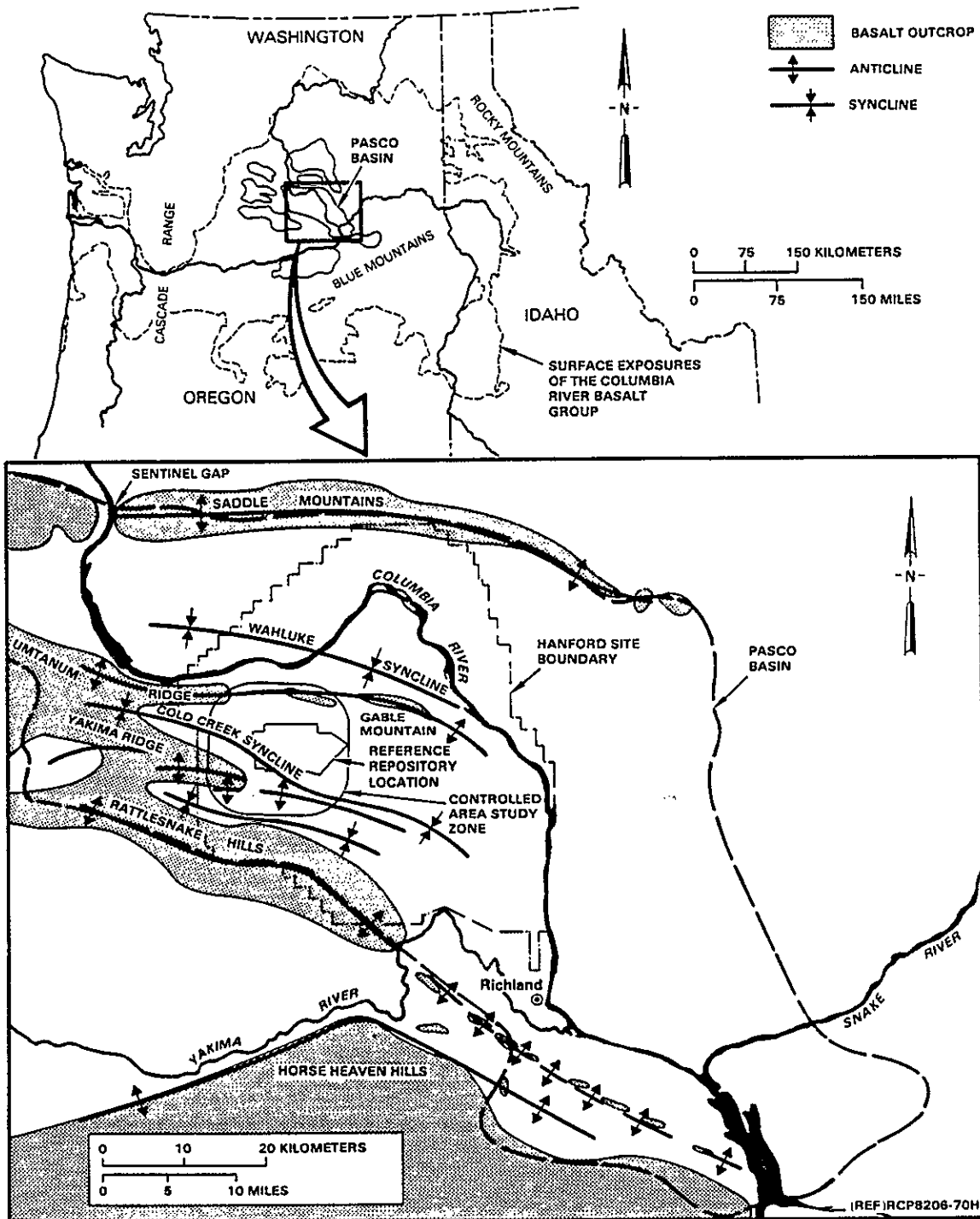


Figure 8.3.1.6-1. Location map.

intrusion into the repository system during possible future resource exploration or exploitation. Strategies to obtain the necessary information and parameters on natural resource potential have been formulated for the following two investigations:

1. Investigation of mineral, hydrocarbon, and geothermal resource potential. This investigation will evaluate potential resources that occur in the Hanford Site. This evaluation requires that the following information be obtained:
 - Available data and analyses concerning known occurrences and past and present production of each resource in the Columbia Plateau.
 - Published economic evaluations of resources within the Columbia Plateau.
 - Available and newly acquired data to be used to define and evaluate geological conditions of each resource.

The information for each resource will be used to evaluate the probability of the particular resource occurring within the controlled area study zone on the Hanford Site. Resource concentrations (quality and quantity) will be estimated for each resource. These will be used to assess the present value of each resource within the controlled area study zone. Also, the resource evaluation of the controlled area study zone will include a comparison of its resource occurrences to other analog areas of similar size and geologic setting. The results of these analyses will provide a basis for estimating the likelihood for postclosure human intrusion of the repository system during possible future resource exploration and exploitation in the controlled area study zone, which could result in an inadvertent loss of waste isolation.

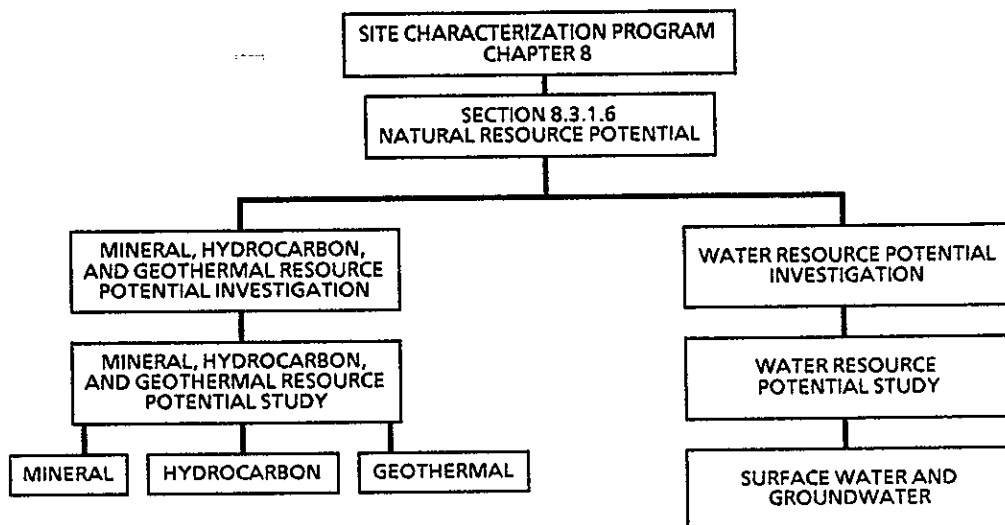
2. Investigation of water resource potential. This investigation will meet the need for understanding whether the development of surface or groundwater resources could affect repository performance. Future development of groundwater resources could alter vertical or horizontal hydraulic gradients, potentially impacting groundwater flow patterns in the controlled area study zone. Development of surface water resources could affect repository performance mainly by interactions with the groundwater system. In order to predict how future water resource activities will alter the regional groundwater system and hydrologic boundary conditions of the controlled area study zone, the following information is needed:
 - Identification of past, present, and potential water resource activities.

- Analysis of sensitivity of the groundwater system to changes in water resource activities.
- Analysis of sensitivity of the groundwater system to changes in water resource development scenarios (i.e., combined water resource activities).

Organization of Section 8.3.1.6

Figure 8.3.1.6-2 indicates the breakdown for the two resource potential investigations. The investigation of mineral, hydrocarbon, and geothermal resource potential (Section 8.3.1.6.3) will provide information to be used in determining whether the exploration and exploitation of naturally occurring resources could affect repository performance. The investigation of water resource potential (Section 8.3.1.6.4) will provide information to be used in determining whether the development of surface or groundwater resources could affect repository performance.

The areas designated in these two investigations range from a small scale (where a large area, such as the Columbia Plateau, is covered in less detail, creating a generalized overview) to a large scale (where a small area, such as the controlled area study zone, is covered in greater detail). The six areas that have been established for the investigations are the following: repository site, controlled area study zone, Cold Creek syncline, Pasco Basin, the Hanford Site, and region. (The region includes the area beyond the Columbia River Basalt Group boundary.) Figure 8.3.1.6-1 portrays these six areas.



PS87-2005-8.3.1.6-1

Figure 8.3.1.6-2. Breakdown of investigations.

8.3.1.6.1 Purpose and objectives

The purpose of the two resource potential investigations is to evaluate the naturally occurring resources of the Hanford Site. Objectives addressed by these investigations are as follows:

- Identification of the mineral, hydrocarbon, and geothermal resource potential of the Hanford Site.
- Assessment of the impacts of potential water resource development on groundwater flow patterns and gradients.

Information from resource potential investigations is critical for an adequate determination of site performance relative to the regulatory requirements related to the potential for inadvertent human intrusion, groundwater travel time, and radionuclide release. Changes in radionuclide release may occur due to human intrusion into the repository during possible future resource exploration or exploitation. Strategies to obtain the necessary information and parameters on resource potential have been formulated and are discussed under both investigations.

8.3.1.6.2 Rationale

An evaluation of the resource potential of the Hanford Site is required to assess the presence of appreciable quantities of naturally occurring material identified as a resource and the potential for human intrusion into the repository system during possible future exploration for and exploitation of natural resources within the controlled area study zone. Justification for obtaining this information is based on the following:

- Regulations 10 CFR 60.122 (NRC, 1987) and 10 CFR 960.4.2.8 (DOE, 1987), which define favorable, adverse, and disqualifying conditions related to natural resource exploration and exploitation; Regulation 40 CFR 191.16 (EPA, 1986), which defines protection of special sources of groundwater.
- Issues and parameters derived to address these regulations (Table 8.3.1.6-1 and Section 8.2). The two resource potential investigations provide input to performance parameters associated mainly with Issues 1.1 and 1.8, and Potentially Adverse Conditions No. 2, 17, and 18. In addition, the water resource potential investigation will provide input to Issue 1.3.

The parameters developed in these investigations support the performance parameters. The performance parameters evolved from the informational needs of the issues and address the general natural resource potential characteristics of the Hanford Site and the region. The supporting parameters provide specific geologic data that help in fulfilling the performance parameters, which in turn are used in resolution of the issues. The

Table 8.3.1.6-1. Parameters addressed by natural resource potential investigations (sheet 1 of 3)

Parameter	Issue	Supporting parameter	Scale/ location	Tentative parameter goal or needed accuracy	Needed confidence	Current estimate	Current confidence	Study	Test/task/analyses
Probability of occurrence of human intrusion (drilling, fluid injection/withdrawal) ^a	1.1			No goal	High				
• Shallow well pumping	1.3	Fixed costs Variable costs	Pasco Basin	No goal	TBD	TBD	TBD	(b)	Water resource development costs
• Surface well pumping	1.3	Fixed costs Variable costs	Pasco Basin	No goal	TBD	TBD	TBD	(b)	Water resource development costs
• Water purification	1.3	Fixed costs Variable costs	Pasco Basin	No goal	TBD	TBD	TBD	(b)	Water resource development costs
• Water distribution	1.3	Fixed costs Variable costs	Pasco Basin	No goal	TBD	TBD	TBD	(b)	Water resource development costs
• Deep well pumping	1.3	Fixed costs Variable costs	Pasco Basin	No goal	TBD	TBD	TBD	(b)	Water resource development costs
• Potential for quantities of metallic and non-metallic minerals in interbeds and suprabasalts (exploration/exploitation)	1.8 (PAC 17)	Previous exploration and production	Region	Identify previous exploration/production	High	Data available for identification	Medium	(c)	Information compilation task
		Identify base and precious metals	Hanford/ CASZ	Identification of base and precious metals	High	Samples available and to be collected for analysis	Low	(c)	Assay tests resource value probability analysis
		Present exploration and production	Region	Identify present exploration/production	High	Data available for identification	Medium	(c)	Monitoring task
		Existing deposits	Region	Identification of existing deposits	High	Data available for identification	Medium	(c)	Information compilation task
		Geologic setting	Region	Ascertain geologic setting	High	Data available for ascertaining geologic setting	Medium	(c)	Information compilation task
		Geologic history	Region	Ascertain geologic history	High	Data available for ascertaining geologic history	Medium	(c)	Analog comparison task
		Present-day value	Hanford/ CASZ	Determine present-day value	High	Data to be collected	Low	(f)	Present-day value analysis (analog comparison)
• Potential for economic quantities of hydrocarbons in interbeds/beneath basalts (exploration/exploitation)	1.8 (PAC 17)	Previous exploration and production	Region	Identify previous exploration/production	High	Data available for identification	Medium	(c)	Information compilation task
		Present exploration potential	Region	Identify present exploration/production	High	Data available for identification	Medium	(c)	Monitoring task
		Sub-basalt stratigraphy and structure	Pasco Basin/ CASZ	Identify sub-basalt stratigraphy and structure	High	Geologic and geophysical data available and to be collected	Low	(c)	Stratigraphic and structural task
		Hydrocarbon evaluation of source rock and reservoir rock	Region	Ascertain source and reservoir rocks	High	Samples to be collected and tested	Low	(c)	Geochemical tests and geophysical tests

PST87-2005-8.3.1.6-1

Table 8.3.1.6-1. Parameters addressed by natural resource potential investigations (sheet 2 of 3)

Parameter	Issue	Supporting parameter	Scale/ location	Tentative parameter goal or needed accuracy	Needed confidence	Current estimate	Current confidence	Study	Test/task/analyses
<ul style="list-style-type: none"> Potential for economic quantities of hydrocarbons in interbeds/beneath basalts (exploration/exploitation) (cont.) 	1.8 (PAC 17) (cont.)	Basin analyses	Pasco Basin	Analyses of basin	High	Data available for analyses	Low	(c)	Burial and thermal analyses
		Hydrocarbon prospects	Region	Identify hydrocarbon prospects	High	Data available and to be collected for prospect identification	Low	(c)	Hydrocarbon potential analysis
		Present-day value	Hanford/ CASZ	Determine present-day value	High	Data to be collected	Low	(c)	Present-day value analysis
<ul style="list-style-type: none"> Potential for economic geothermal resources (exploration/exploitation) 	1.8 (PAC 17)	Previous exploration/production	Region	Identify previous exploration/production	High	Data available for identification	Medium	(c)	Information compilation task
		Present exploration/production	Region	Identify present exploration/production	High	Data available for identification	Medium	(c)	Monitoring task
		Geothermal gradient	Region/ CASZ	Ascertain geothermal gradient	High	Data available for ascertaining geothermal gradient	Medium	(c)	Temperature analysis
		Geothermal environment	Region	Ascertain geothermal environment	High	Data available for ascertaining geothermal environment	Medium	(c)	Temperature analysis
		Thermal conductivity of stratigraphic section	Region	Identify thermal conductivity of stratigraphic section	High	Samples to be collected and tested	Low	(c)	Thermal conductivity tests
		Heat flow	Region	Ascertain heat flow	High	Data available and to be collected for analysis	Low	(c)	Heat flow analysis
		Geothermal prospects	Region	Identify geothermal prospects	High	Data available and to be collected for prospect identification	Low	(c)	Geothermal potential analysis (analog comparison)
		Present-day value	Hanford/ CASZ	Determine present-day value	High	Data to be collected	Low	(c)	Present-day value analysis
Hydraulic gradient across the CASZ a, d	1.1		Region/ CASZ	Head value ± 2 m (6.6 ft) Flux value $\pm 20\%$					
<ul style="list-style-type: none"> Hydraulic flux across CASZ boundaries 	1.8 (PAC 2)	Population projections	Pasco Basin/ CASZ	Project populations	High	Data available to project populations	Medium	(b)	Identification of water resource activities
		Groundwater demand	Pasco Basin/ CASZ	Identify groundwater demand	High	Data available to identify groundwater demand	Low	(b)	Identification of water resource activities
		Projected cropland distribution for irrigation	Pasco Basin/ CASZ	Project cropland distribution for irrigation	High	Data available to project cropland distribution for irrigation	Low	(b)	Identification of water resource activities
		Crop or land cover	Pasco Basin/ CASZ	Identify crop or land cover	High	Data available for identification	Low	(b)	Identification of water resource activities
		Surface water availability for increased irrigation	Pasco Basin/ CASZ	Identify surface water availability for increased irrigation	High	Data available to identify surface water availability	Low	(b)	Identification of water resource activities

PST87-2005-8.3.1.6-1

Table 8.3.1.6-1. Parameters addressed by natural resource potential investigations (sheet 3 of 3)

Parameter	Issue	Supporting parameter	Scale/ location	Tentative parameter goal or needed accuracy	Needed confidence	Current estimate	Current confidence	Study	Test/task/analyses
● Hydraulic flux across CASZ boundaries (cont.)	1.8 (PAC 2) (cont.)	Probability of fluid waste injection	Pasco Basin/ CASZ	Determine probability of fluid waste injection	High	Data available to determine probability	Low	(b)	Identification of water resource activities
		Predicted volume of fluid waste injection	Pasco Basin/ CASZ	Predict volume of fluid waste injection	High	Data available	Low	(b)	Identification of water resource activities
		Predicted composition of fluid waste	Pasco Basin/ CASZ	Predict composition of fluid waste	High	Data available	Low	(b)	Identification of water resource activities
		Predicted stratigraphic horizon of fluid waste injection	Pasco Basin/ CASZ	Predict stratigraphic horizon of fluid waste injection	High	Data available	Low	(b)	Identification of water resource activities
● Borehole probabilities	1.8 (PAC 2)	Probability of groundwater boreholes as a function of time	Pasco Basin/ CASZ	Develop probability distribution	High	Based on current data available to define probability distribution	Low	(b)	Identification of water resource activities
● Probability of dam construction	1.8 (PAC 2)	Energy demand	Region	Determine probability	High	Data to be collected to determine probability	Low	(b)	Identification of water resource activities
● Geothermal production	1.8 (PAC 2)	Geothermal potential	CASZ	Identify geothermal potential	High	Data available and to be collected to identify geothermal potential	Low	(c)	Geothermal potential analysis
● Hydrocarbon production	1.8 (PAC 2)	Hydrocarbon potential	CASZ	Identify hydrocarbon potential	High	Data available and to be collected to identify hydrocarbon potential	Low	(c)	Hydrocarbon potential analysis

NOTE: CASZ = Controlled area study zone.

PAC = Potentially adverse condition.

^aPerformance parameter (Issue 1.1) supported by issues and parameters listed below.^bWater resource potential study.^cMineral, hydrocarbon, and geothermal resource potential study.^dThese parameters will be determined by the indicated studies and analyses in conjunction with other studies (e.g., regional groundwater study).

PST87-2005-8.3.1.6-1

relationship between the performance and the supporting parameters, as well as the associated issues, are indicated in Table 8.3.1.6-1. This table also lists the goals and accuracies required for the various parameters.

Implicit to these investigations is the assumption that the value to future generations of potential resources can be assessed adequately from information available at the present time.

8.3.1.6.3 Investigation of mineral, hydrocarbon, and geothermal resource potential

Reports on resources that occur in the vicinity of the site are discussed in Section 1.7. These reports were used to develop the baseline for the resources that are presently known to occur within the Columbia Plateau. These reports were also used to focus on one study (of the same name as the investigation) with three components (see Fig. 8.3.1.6-2). The three components are listed below.

- Metallic, nonmetallic, and fuel minerals (Section 8.3.1.6.3.3.1).
- Hydrocarbon resources (Section 8.3.1.6.3.3.2).
- Geothermal resources (Section 8.3.1.6.3.3.3).

8.3.1.6.3.1 Purpose and objectives

The purpose of this investigation is to evaluate the potential for the presence of mineral, hydrocarbon, and geothermal resources at the Hanford Site. Objectives of this investigation are as follows:

- Identification of known occurrences and past and present production of each resource in the Columbia Plateau.
- Review of economic evaluations of resources within the Columbia Plateau.
- Identification of the quality and quantity of resources at the Hanford Site using available and newly acquired data.

The geological, geophysical, and geochemical information for each resource will be used to evaluate the probability of the particular resource occurring within the controlled area study zone on the Hanford Site. The resource concentrations (quality and quantity) estimated for each resource will be used to assess the present value of each resource within the controlled area study zone. The resource evaluation of the controlled area study zone will include a comparison of the resource occurrences to other analog areas that share a similar size and geologic setting with the controlled area study zone. The results of these analyses will provide input to performance assessment to determine the probability for human intrusion into the repository during future exploration or exploitation of natural resources.

8.3.1.6.3.2 Rationale

The mineral, hydrocarbon, and geothermal resource potential investigation was developed to meet the need for understanding the resource potential of the Hanford Site.

The principal technical concern of this investigation is to provide quantitative and qualitative evaluations of the natural resource potential. These evaluations will be used in the performance assessment to estimate relative probabilities for and consequences of human activity scenarios that could significantly affect repository performance. Data to solve this technical issue will come from a combination of borehole, geophysical, and geologic surveys and evaluations and observations of potential resources in the vicinity of the site. Some data are in hand, other data will come from the investigation. These data will permit inferences to be drawn regarding geologic conditions at depth and the likelihood of potential natural resources that may be explored for or exploited in the future.

This investigation will utilize existing data together with information from industry exploration activities and from data collected by the Basalt Waste Isolation Project (BWIP). The BWIP data collection tasks focus on supplementing the existing data set to enhance the evaluation of resource potential for the Hanford Site. The following two data collection tasks are planned:

- Obtaining geologic information on prebasalt sediments gathered from the basalt margin (to identify the margin stratigraphy and structures that may extend beneath the basalts). This task includes sampling of outcrop and obtaining deep well data to determine reservoir, source rock, seal and thermal maturation properties relative to hydrocarbon occurrences, and thermal conductivity rock properties relative to geothermal occurrences.
- Acquiring seismic reflection data and surveys that could assist in the evaluation of deep subsurface structures. The BWIP will acquire surveys and consider purchasing any available pertinent lines.

In addition, consideration is also being given to drilling a deep, multipurpose exploration borehole into sub-basalt sediments that could enhance the evaluation of hydrocarbon and geothermal resource potential of the Hanford Site. The Hanford Site is restricted Federal land where no deep exploration drilling has occurred. The principal constraint on the resource potential investigation is that the subsurface occurrences of any potential mineral resources within the controlled area study zone cannot be observed directly. The data collection is constrained by borehole locations and availability of core samples. The need for a deep, multipurpose borehole to improve the evaluation of the resource potential at the controlled area study zone is being considered and a position paper is being prepared by the BWIP. In addition, data from the deep, multipurpose borehole would be utilized by hydrochemistry, rock deformation, mineralogy and petrology, structure, and geochemistry studies. This deep, multipurpose exploratory borehole would be

drilled through the Columbia River Basalt Group and into the sub-basalt sediments (approximately 6,100 m (20,000 ft) total depth). Selection of a synclinal position or offstructure location for the borehole within or near the controlled area study zone would provide information on the hydrocarbon potential in the same expected geologic setting as the repository site. The deep borehole may be similar to a deep stratigraphic test well (the official regulatory term referring to a continental offshore stratigraphic test (COST) well). The COST wells are drilled on unleased Federal lands in basins where no deep drilling has occurred. These wells are drilled to gather information about the stratigraphic formations present, the general character of the rocks, their porosity and permeability, and their organic content.

8.3.1.6.3.3 Description of study

The single study under this investigation (both have the same title) will provide information on the occurrences of natural resources (excluding water resources) within the Hanford Site. This study is divided into three components (see Fig. 8.3.1.6-2). The tasks, tests, and analyses associated with each of these components are discussed in this section. They are described in greater detail in the mineral, hydrocarbon, and geothermal resource potential study plan.

In addition, oil and gas lease holdings, geologic and geophysical activity, and drilling activity will be monitored. These activities will be recorded on maps, thus providing a record of competitive industry activity in areas adjacent to the Hanford Site. Mining activity that occurs in the vicinity of the site will also be monitored and recorded on maps.

The objective of this study is to evaluate the potential natural resources at the Hanford Site. This study is divided into the following three components:

1. Metallic minerals (base and precious metals); nonmetallic minerals (clay, diatomaceous earth, perlite, pumice and pumicite, sand, gravel, and stone); and fuel minerals (coal, peat, and uranium).
2. Hydrocarbon resources (oil and gas).
3. Geothermal resources (low temperature).

Parameters addressed by the study are listed in Table 8.3.1.6-1. The tasks, tests, and analyses for this study are listed in Table 8.3.1.6-2. Each component of the study is described in the following sections.

8.3.1.6.3.3.1 Metallic, nonmetallic, and fuel minerals component.

An evaluation of these resources has been previously performed by the BWIP Geosciences Group and George Leaming Associates (GG/GLA, 1981) for the immediate vicinity around the Hanford Site, adjacent counties, and the Columbia Plateau (discussed in Section 1.7). At the time of publication of

Table 8.3.1.6-2. Tasks, tests, analyses for mineral, hydrocarbon, and geothermal natural resource potential study (sheet 1 of 3)

Tasks/tests/analyses	Methods	Location/scale	Number of tests	Information for analyses	
				Data	Results
Mineral component 8.3.1.6.3.3.1					
● Information compilation task	Research literature for new publications	As appropriate/region	--	Published reports, studies, evaluations, surveys, etc.	Library of published data
● Monitoring task	Plot input from information compilation task	Where appropriate/region	--	Mineral resource locations and mining activities	Map with resource locations and mining activities plotted
● Mineral resource occurrence task	Collect samples from borehole core/outcrop: x-ray diffraction, x-ray fluorescence, and petrographic analysis	From interbeds of 12 boreholes and outcrop/ Pasco Basin	--	Borehole core/outcrop samples	Mineral resource occurrence in CASZ
● Assay test	Standard laboratory practice for precious and base metal assays	From interbeds of 12 boreholes and outcrop/ Pasco Basin	Borehole: 50-100 Outcrop: To be determined	Precious and base metal assays	Quality-quantity of precious and base metal minerals
● Resource value probability analysis	Probability determination of mineral resource occurrences	--	--	Mineral resource occurrence in Hanford Site	Mineral resource occurrence in CASZ
● Analog comparison task	Input from information compilation and mineral resource occurrence tasks; observational	As appropriate/Columbia plateau	--	Mineral resource occurrence in CASZ and analog areas	Comparison of CASZ with analog areas
● Present-day resource value analysis	Input from all tasks: to determine present-day value of known and potential mineral resources occurrences	--	--	Values of mineral occurrences in Hanford Site and region	Present-day value of mineral occurrences in CASZ
Hydrocarbon component 8.3.1.6.3.3.2					
● Information compilation task	Research literature for new publications	As appropriate/region	--	Published reports, studies, evaluations, surveys, etc.	Library of published data
● Monitoring task	Plot information from compilation task	Where appropriate/region	--	Geologic/geophysical surveys, drilling, testing activities	Map with oil industry activities plotted
● Stratigraphy and structure task	Integrate geologic and geophysical data, interpret	Region	--	Basalt margin geology, data from deep wells, geophysical surveys	Establish sub-basalt stratigraphy and structure depicted with stratigraphic column and cross section of Pasco Basin
● Hydrocarbon evaluation task	Collect and select samples	As appropriate/region	--	Samples from basalt margin, deep wells	Samples of potential source and reservoir rocks
● Geological/geophysical/geochemical tests	Standard laboratory practice for source and reservoir rock characteristic testing	As appropriate/region	Outcrop: as appropriate Deep wells: As appropriate	Total organic carbon, rock-eval, kerogen type, R _o , porosity, permeability	Source and reservoir rock properties of sedimentary sequence beneath basalt
● Wireline log analyses	Industry practice for wireline log analyses	--	--	Wireline logs from deep wells that are available	Identification of physical rock properties and stratigraphy

PST87-2005-8.3.1.6-2

Table 8.3.1.6-2. Tasks, tests, analyses for mineral, hydrocarbon, and geothermal natural resource potential study (sheet 2 of 3)

Tasks/tests/analyses	Methods	Location/scale	Number of tests	Information for analyses	
				Data	Results
Hydrocarbon component 8.3.1.6.3.3.2 (cont.)					
• Burial history and thermal history analyses	Plot burial and thermal paths of sediments in deep wells	As appropriate/region	--	Stratigraphic units, ages, temperature gradients from deep wells	Burial history and thermal history of sediments in deep wells; maturation of source rocks
• Rattlesnake hills gas field task	Incorporate compiled published well data and associated reports	Rattlesnake Hills/region	--	Stratigraphic units (depths and thickness), structure, well locations	History of gas production; stratigraphy, structures, reservoir, traps identified; cross section and map of gas field
• Gas test	Standard laboratory practice for isotopic testing of gas	--	One test/sample	Chromatographs of gas	Isotopic identification of gas
• Hydrocarbon resource potential task	Make structure and stratigraphic structure contour maps, interpret	As appropriate/region	--	Geologic and geophysical maps	Identify hydrocarbon prospects for exploration
• Analog comparison task	Input from hydrocarbon resource potential task	As appropriate/region	--	Boreholes drilled in synclines through sub-basalt sediments	Analog area identified to compare with the CASZ
• Present-day resource value analysis	Input from all tasks to determine present-day values	--	--	Value of hydrocarbon resources in Hanford Site and region	Present-day value of hydrocarbons in CASZ
Geothermal component 8.3.1.6.3.3.3					
• Information compilation task	Research literature for new publications	As appropriate/region	--	Published reports, studies, evaluations, surveys, etc.	Library of published data
• Monitoring task	Plot input from information compilation task	Where appropriate/region	--	Geothermal resource locations	Map with geothermal resource locations
• Temperature analysis	Input from information compilation task	Region	--	Temperature data from boreholes, deep wells, areal temperature surveys	Thermal map of region, isothermal map
• Thermal conductivity measurement test	Standard laboratory practice for thermal conductivity test	--	One test/sample	Cuttings from deep wells, samples from basalt margin sediments	Thermal conductivity measurements for stratigraphic section of sub-basalt sediments
• Heat flow analysis	Input from temperature analyses and thermal conductivity test	As appropriate/region	--	Temperature data; thermal conductivity measurements	Heat flow maps for Hanford Site and CASZ
• Geothermal potential analysis	Input from heat flow analysis and structure map	--	--	Heat flow analysis map, surface structure map	Identification of heat flow and surface structure trends for geothermal resource potential

PST87-2005-8.3.1.6-2

Table 8.3.1.6-2. Tasks, tests, analyses for mineral, hydrocarbon, and geothermal natural resource potential study (sheet 3 of 3)

Tasks/tests/analyses	Methods	Location/scale	Number of tests	Information for analyses	
				Data	Results
Geothermal component 8.3.1.6.3.3.3 (cont.)					
<ul style="list-style-type: none">● Analog comparison task	Input from geothermal potential analysis	As appropriate/Columbia plateau	--	Heat flow analysis map, surface structure map	Analog area identified to compare with CASZ
<ul style="list-style-type: none">● Present-day resource value analyses	Input from all tasks to determine present-day values	--	--	Value of geothermal resources in Hanford Site and region	Present-day value of geothermal resource in CASZ

NOTE: CASZ = Controlled area study zone.

PST87-2005-8.3.1.6-2

this report, exploitation of these resources within 100 km (62 mi) of the Hanford Site was limited to surface mining operations that produce diatomaceous earth, sand, gravel, and crushed stone. There is no present exploitation of clay, perlite, pumice and pumicite, precious and base metals, coal, peat, or uranium within a 100 km (62 mi) radius of the site (see Fig. 1.7-1).

In order to supplement published mineral resource reports and evaluations that do not include data from within the Hanford Site, this component has been developed to determine the occurrence, quantity, and quality of mineral resources within the Hanford Site. The Columbia River Basalt Group has been evaluated physically and chemically (over 10,000 chemical analyses have been performed) by the BWIP. Because no unique or unusual resource potential minerals have been found in the basalts, the mineral component will focus on the resource potential of the interbedded sediments (members of the Ellensburg Formation) between the basalt flows and the suprabasalt sediments. However, if future coring in the basalt flows encounters mineralized zones, assays will be performed on those zones to determine the quality and quantity of the mineralization.

The tasks, tests, and analyses identified with this component are listed in Table 8.3.1.6-2 and described below.

Information compilation task--The objective of this task is to update resource information, as necessary, with newly published reports, evaluations, or studies on mineral resources in the region. This includes reports on exploration and production and new deposits as well as any new publications on the geologic setting and history of the region. Existing deposits have been identified and previous exploration and production have been described in the literature published by the Federal, state, and county governments, as well as in studies by consultants to the BWIP.

Monitoring task--The objective of this task is to monitor ongoing industry activity in the region. Maps will be used to show the location of mining production and mineral exploration (drilling, geologic, or geophysical surveys). The information for these activities will be obtained from the compiled resource information.

Mineral resource occurrence task--The objective of this task is to identify the occurrences of mineral resources in the interbeds on the Hanford Site and to establish the quantity and quality of these occurrences. Initially, 12 boreholes have been selected, and other boreholes may be used, if necessary. Core samples of the interbed sediments will be taken from boreholes that have already been drilled on or near the Hanford Site. Figure 8.3.1.6-3 locates the specific boreholes that will be utilized in evaluating the resource minerals at the site. These 12 boreholes (DC-2, DC-4, DC-6, DC-8, DC-12, DC-15, DC-16, DC-18, DH-4, DH-5, RRL-2, RRL-6) have been selected for sampling by the mineralogic and petrologic characterization study (Section 8.3.1.2.5.3) and the stratigraphy study (Section 8.3.1.2.3.3.1) to identify the interbed mineralogy and will be used in the development of the interbed stratigraphy. Typically, samples will be taken from the top, bottom, and middle of each interbed encountered in the borehole. The exact number of

samples will vary per interbed (and thus per borehole), depending on the thickness of the bed. It is estimated that between 100 and 200 samples will be taken from cores from the 12 boreholes to be used by these two studies. The sampling interval per interbed will range from 0.09 to 0.18 m (0.3 to 0.6 ft). Test methods employed to identify the mineralogy will be whole rock x-ray diffraction, x-ray fluorescence, and petrographic analyses of the collected samples. More detailed information on the test methods can be found in the stratigraphy study (Section 8.3.1.2.3.3.1), the Mineralogic and Petrologic Characterization Study Plan (Horton, 1987), and the Mineral, Hydrocarbon, and Geothermal Resource Potential Study Plan (Moses, 1987).

The suprabasalt sediments have been mapped on the Hanford Site and their stratigraphic units have been described by the BWIP (Myers and Price, 1981). Methods of correlations of the interbeds and the suprabasalt sediments are described in Sections 8.3.1.2.3.3.1 and 1.2.2.2 and the Stratigraphy Study Plan (Landon, 1987). The cross sections and geologic map resulting from the stratigraphic study of the suprabasalt sediments will be used to identify locations for sampling. The most likely sections for sampling are the coarse-grained basal and middle units of the Ringold Formation. The Ringold Formation is derived from ancestral Columbia and Snake River drainage systems (Fecht et al., 1984) that have drained from mineral-rich provinces located on the perimeter of the Columbia Plateau. In addition, test methods employed by the stratigraphy study to correlate the interbedded sediments and the suprabasalt sediments will be useful in identifying anomalous concentrations of minerals (i.e., anomalous to the baseline minerals that were identified from previous resource potential mineral evaluations). Quality (e.g., grade or rank) and quantity of any nonmetallic or fuel minerals that are identified in the interbeds or in the suprabasalt sediments as the result of the stratigraphic and mineralogic and petrologic characterization studies will be determined as appropriate to the type of mineral occurrence.

Assay test--To supplement the work that has been done or work that will be done by the mineralogic and petrologic characterization study and the stratigraphy study, assay tests will be made for gold, silver, and uranium on selected samples from interbeds and suprabasalt sediments from the same boreholes used by these studies (see Fig. 8.3.1.6-3). These particular minerals are being considered because they have been reported in the literature as occurring in the vicinity of the Hanford Site. In addition, assays for base metals may be made on selected samples from these boreholes if warranted. The tests will follow standard contractor procedures for assaying base and precious metals.

Resource value probability analysis--This analysis, using information obtained from the mineral resource occurrence task (locations of resource occurrences, concentrations, etc.), is a model to determine the probability of the known resources that occur in the Hanford Site for occurrences in the controlled area study zone. The results from this analysis will be used in the analog comparison task.

Analog comparison task--This task will compare the known occurrences of minerals from the Hanford Site to analog areas in the region. The selected analog will share a similar size and geologic setting with the controlled area study zone. The information will be used to evaluate the potential for mineral exploration at the site and to further define the known mineral deposits that might be expected.

Present day resource value analysis--This analysis will use information from all of the other tasks to determine the present-day value of the known and potential occurrences of mineral resources on the Hanford Site and in the controlled area study zone. The results from this analysis will provide input to performance assessment to determine the probability for human intrusion into the repository during future exploration or exploitation of natural resources.

8.3.1.6.3.3.2 Hydrocarbon resource potential component.

A preliminary evaluation of the hydrocarbon resource potential of the Hanford Site was made in GG/GLA (1981). The evaluation of the hydrocarbon resources within the sub-basalt sediments made in this report was based only on data obtained from the Development Associates Basalt Explorer No. 1 well near Odessa, Washington. Subsequent to the publication of the GG/GLA (1981) report, the Shell Oil Company has drilled four wells within the Columbia Plateau that penetrated the sub-basalt sediments. The drilling results for three of these wells are discussed in Section 1.7.2.2 and by Campbell (1985) and Lingley and Walsh (1986). The drilling data from the most recently completed Shell well (the Saddle Mountain BN No. 1-9) has been released by Washington State and will be evaluated by the BWIP during site characterization. The Columbia Basin exploratory wells are identified in Figure 8.3.1.6-4 and Table 8.3.1.6-3.

A geologic understanding of the Columbia Plateau sub-basalt sediments is important to the evaluation of the hydrocarbon resource potential within the Hanford Site. Only seven wells in the Columbia Plateau penetrate the sub-basalt sediments, and only two of these seven bottomed in probable basement (see Fig. 8.3.1.6-4 and Table 8.3.1.6-3). The data on the sub-basalt geology are therefore limited, and a comprehensive evaluation of the hydrocarbon resource potential will require an integration of the available geologic and geophysical data. The integration of geologic and geophysical data, interpretations, and analyses must be performed in order to provide the following information important for evaluation of the hydrocarbon resource potential within the Hanford Site:

- Depositional basin configuration and development with time.
- Depth to the basalt/sub-basalt sediment and sub-basalt sediment/basement contacts.
- Thickness and lateral extent (approximate volume) of the sub-basalt sediments.

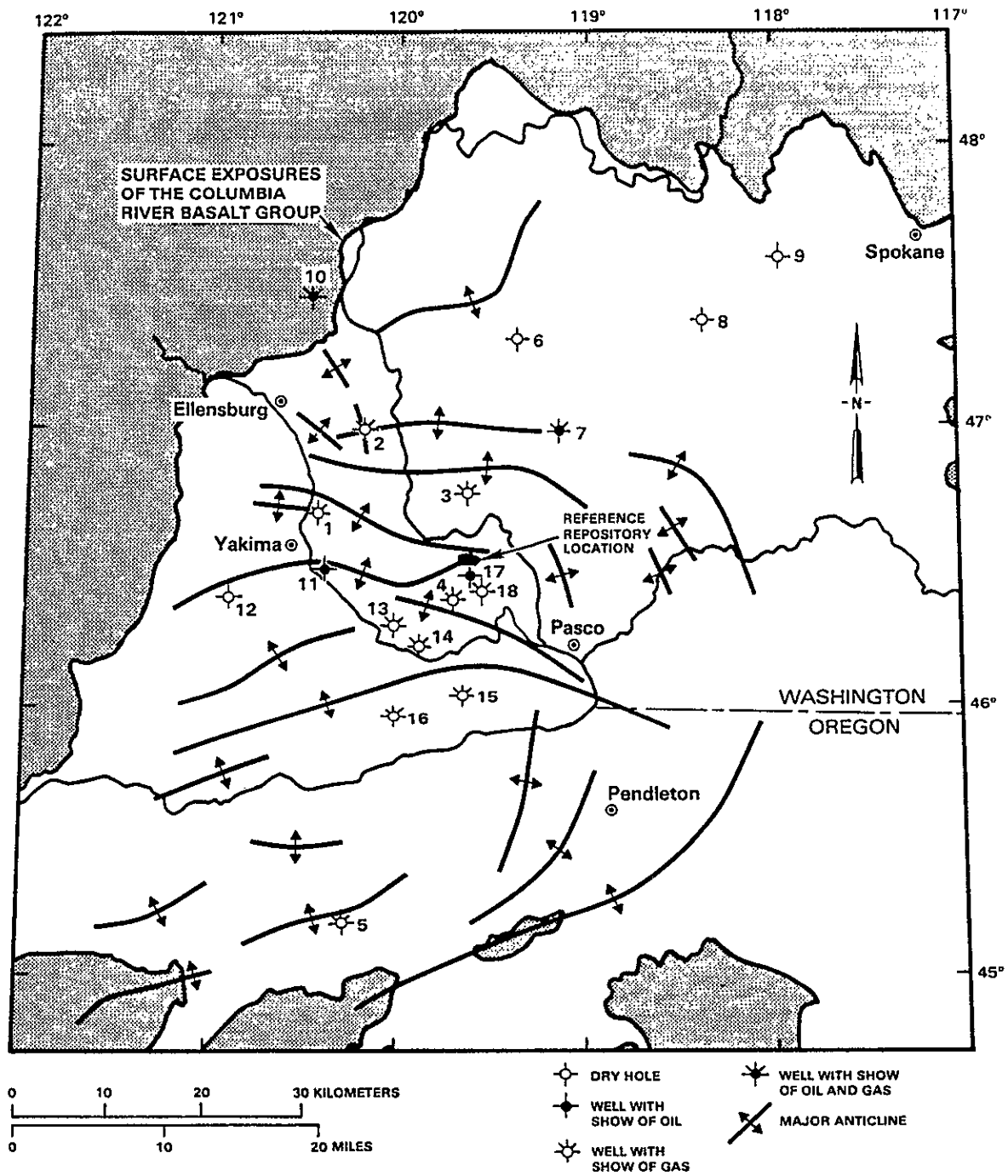
Table 8.3.1.6-3. Columbia Basin exploratory wells

Well No. ^a	Well name	Geologic structure	Total depth		Year drilled	Comments: reported oil/gas shows
			Meters	Feet		
1 ^b	Shell Oil Company	Selah Butte anticline	4,939	16,199	1980	Gas
1 ^b	Yakima Minerals Well No. 1-33	Selah Butte anticline	1,007	6,600	1981	Gas
2 ^{b,d}	Bissa No. 1-29	Whiskey Dick anticline	4,562	14,965	1982	Gas
3 ^b	BN No. 1-9	Saddle Mountains anticline	5,341	17,518	1983	Gas (3.5 mcf/d) ^c
4	Standard Oil Company Rattlesnake Unit No. 1	Rattlesnake Hills anticline	3,248	10,655	1958	Gas
5 ^b	Kirkpatrick No. 1	Condon anticline	2,660	8,726	1956	No shows
6	Snowbird Resources Moses Lake No. 1a	Unknown	2,128	6,979	1981	No shows
7	Peoples Gas and Oil Development Co. Donney Boy No. 1	Frenchman Hills anticline	1,394	4,575	1934	Gas
8 ^{b,e}	Development Associates Inc. Basalt Explorer No. 1	Unknown	1,427	4,682	1965	No shows
9	Delta Gas and Oil Company Inc. Alt No. 1	Unknown	402	1,320	1960	No shows
10 ^b	Norco First Drilling Company Norco No. 1	Unknown	1,494	4,903	1933	Gas, oil
11	Miocene Petroleum Company Union Gap	Ahtanum anticline	1,161	3,810	1929	Gas, oil
12	Simco Oil Company Simco No. 1	Ahtanum anticline	841	2,760	1924	No shows
13	Paul John Hunt Snipes No. 1	Snipes Ridge anticline	429	1,408	1944	Gas
14	City of Mabton No. 1	Unknown	347	1,140	1922	Gas
15	Columbia Hydrocarbon Moon No. 1	Unknown	501	1,645	1982	Gas
16	Blue Light Gas and Oil Company Alder Creek No. 1	Unknown	471	1,545	?	Gas
17	Scott Drilling Company Benson Ranch	Benson Ranch syncline	610	2,000	1929	Oil
18	Rattlesnake Hills gas field - discovery well Conservative Land and Development Co., Walla Walla No. 1	Rattlesnake Hills anticline	376	1,234	1913	Gas (500 mcf/d) ^c

^aSee Figure 8.3.1.6-4 for well location maps.^bWell penetrated sub-basalt sediments.^cmcf/d = 28.32 m³/d.^dBottomed in probable basement.^eBottomed in granite basement.

mcf = Thousand cubic feet.

PST88-2014-8.3.1.6-1



PS8708-40A

Figure 8.3.1.6-4. Location map for Columbia Basin exploration wells.

- Timing and geometric development of folding, faulting, and major structures.
- Principal lithologies and their areal and stratigraphic relationships (especially unconformities).
- Source and reservoir rock properties and characteristics.
- Burial and thermal histories of sub-basalt sediments in the deep wells.
- Sampling of natural gas from wells within the Rattlesnake Hills Gas Field to determine type and possible source generation of gas produced within the basalt section.

The hydrocarbon resource component of this study was developed in order to obtain the information listed above. A position paper is being prepared by the BWIP for the drilling of a deep borehole through the sub-basalt sediments to enhance the hydrocarbon resource potential evaluation (Fig. 8.3.1.6-5 and Table 8.3.1.6-4). A number of tasks, tests, and analyses of geologic, geochemical, and geophysical data identified with this component are listed in Table 8.3.1.6-2 and described below.

Information compilation task--The objective of this task is to update resource information, as necessary, with newly published reports or studies on hydrocarbon resources in the region. These include reports on production or testing from wells and exploration or leasing activity. Previous exploration and production have been identified in the literature published by the Federal, state, and county governments, as well as studies by consultants to the BWIP. In addition, the geologic setting and geologic history have been described extensively in the published literature.

Monitoring task--The objective of this task is to monitor ongoing industrial activity surrounding the site and within the Columbia Plateau. Maps will be used to show the location of the drilling and testing of wells, geologic or geophysical surveys, and any reported hydrocarbon seeps and shows. The information for these activities will be obtained from the compiled resource information task.

Stratigraphy and structure task--The data for sub-basalt geology is limited; thus, an integrated geologic and geophysical approach is necessary to maximize the interpretation of sub-basalt stratigraphy and structure. Geologic data available for use in characterization of sub-basalt sediments include available lithologic-mud logs and reports on the few deep wells that penetrate the sediments. Published reports on rocks of equivalent age that outcrop on the perimeter of the basalts will be used in conjunction with the available deep well data to develop a stratigraphy for the sub-basalt sedimentary section. Specific units for source, seal, and reservoir rock characteristics will be identified within the stratigraphy. Geophysical data acquired within the Columbia Plateau will be used in interpreting sub-basalt sediment thickness and structure. The data used for the interpretation will

come from deep seismic refraction and reflection surveys; regional and detailed gravity and magnetic surveys; magnetotelluric surveys; and borehole geophysical and other geophysical surveys. These geophysical survey data have been or will be obtained from the published literature, public domain data from state and Federal agencies, data acquired by the BWIP, and any other available source of relevant data. Attempts to purchase proprietary data will be made by the BWIP.

Hydrocarbon evaluation task--Samples for testing source, seal, and reservoir rock characteristics will be selected from prebasalt sedimentary rock units from the basalt margin and from samples obtained from the deep wells that penetrated sub-basalt sediments. The Eocene nonmarine sedimentary units are exposed in the Wenatchee Mountains along the northwestern margin of the plateau and in the Blue Mountains of central Oregon along the southern margin of the plateau. The units in the Wenatchee Mountains include the Wenatchee, Chumstick, Roslyn, Swauk, and Manastash Formations. The units in the Republican graben include the O'Brien Creek Formation and Sanpoil volcanics with intercalated arkosic sandstone beds. In the Blue Mountains the Herran Formation and the lacustrine facies of the Clarno Formation are of principal interest to basin studies. Marine Cretaceous strata in the Methow graben of northern Washington and central Oregon inliers will also be sampled. These units are described in greater detail in Section 1.2. The results from testing will supplement the present data base and will be used to define the source, seal, and reservoir rock properties of the sedimentary sequence that trends beneath the basalts.

Geochemical, geological, and geophysical tests--The results from the following list of tests will define the source and reservoir rock properties of the sedimentary sequence that trends beneath the basalts:

Source rocks

- Total organic carbon testing will determine the relative richness of organic content of the sample.
- Rock-Eval (pyrolysis) testing will be performed on all samples with a greater than 0.5% total organic carbon and will yield information about the type of organic material present and its level of maturation. The 0.5% total organic carbon value is the lower threshold value for source rocks by convention in the oil industry.
- Kerogen type testing will indicate the propensity for oil and (or) gas generation of the source samples.
- Vitrinite reflectance (R_o) testing will measure thermal alteration of organic matter and will be used as an index of degree of maturity of the organic material. Typically, higher reflectance values are indicators of greater thermal alteration.

Reservoir rocks

- Porosity testing will measure the ratio of the volume of all pore spaces to the total bulk volume of a rock sample expressed as a per cent of total volume.
- Permeability testing will measure the capacity of the rock for transmitting a fluid. The degree of permeability depends upon the size and shape of the pores, the size and shape and extent of their interconnections, and the mineralogy of the rock matrix.
- Thin sections will be used to determine the characteristics of any cement present and if the porosity is primary or secondary.

Wireline log analysis--The wireline logs from the deep wells will be analyzed to identify the physical rock properties of the lithologic units encountered in the basalt, intrabasalt, and sub-basalt sections and to ascertain any other stratigraphic information about these units. In addition, wireline logs from the Rattlesnake Hills Unit No. 1 will be analyzed.

Burial history and thermal history analyses--The burial history analysis of the deep wells will be performed whereby burial paths of sediments are plotted from their deposition to their present depth through geologic time. As a sediment is buried deeper, it passes through higher temperatures. By assuming a linear thermal gradient with depth that does not change through time, the temperature of the sediments can be identified at any time. In addition, vitrinite reflectance data can be used to identify possible changes of temperature through time (i.e., nonlinear). This type of information would also be used in the analyses. The kerogen in the source rocks tracing this burial path is eventually cracked to form hydrocarbons as a function of both time and temperature. The burial path can be used to relate time and temperature to hydrocarbon generation windows. These hydrocarbon generation windows have been developed as time-temperature and thermal alteration indices. Thus, the kerogen (i.e., the source rock) can be identified when it enters the oil generation window and when it enters the gas generation window.

Rattlesnake Hills gas field task--The objective of this task is to identify the producing reservoir or reservoirs, seals, carrier beds (porous and permeable beds through which hydrocarbons can migrate long distances from the place of generation to the place of entrapment), and other possible paths of migration of the gas in the Rattlesnake Hills gas field. This task will incorporate the compiled published well data and associated reports on the gas field to produce a history of gas production for the field. The stratigraphy, structures, reservoirs, and traps will be identified. A cross section and maps (which may include a structure contour map, productive horizon, etc.) of the field will be produced.

Gas test--The objective of this test is to identify the source or sources for the gas in the Rattlesnake Hills gas field. Gas samples will be collected from the gas field. Previously published test results from some of the wells in the field indicate a high percent of methane and a smaller percent of

9 2 1 2 5 5 0 3 6 1

nitrogen. Some test results indicate the presence of heavier hydrocarbon gases. The various test results reported may represent either different source rocks and different reservoirs or mixing of gases from different sources in one reservoir. The methods being considered, in order of increasing data quality, for collecting gas samples for testing include sampling the atmosphere above the wells, reentering one or more wells, and drilling a borehole (approximately 366 m (1,200 ft)) in the field. Gas chromatography testing characterizes the solvent-soluble organics in rock materials by separating volatile mixtures and registering their presence and relative concentrations. The geochemical testing of carbon and hydrogen isotopes will provide information on the biogenic or thermogenic origin of the gas. If the gas is methane and is biogenic this would suggest a local source, such as degassing of coals (especially if there is a large percent of nitrogen present). If the methane is thermogenic, it may represent dry gas that either has migrated from depth, possibly from sediments that have been heated beyond the oil generation window, or has migrated from depth but was produced from source rocks that only produce methane (Type III kerogen). The testing will yield information on the gas that may be useful in determining the possible source or sources for the gas. This information may be linked with information from the hydrochemistry study on the groundwater flow system.

Analog comparison task--A comparison of the controlled area study zone to an analog area for hydrocarbon potential is not possible because no deep wells have been drilled in a topographically expressed syncline on the Columbia Plateau. The topographic expression of a syncline assumes that the structural configuration of the sub-basalt sedimentary rocks can be determined by the present structure of the overlying basalts. The likelihood for any oil industry company to drill on a syncline in the search for oil and gas is extremely unlikely since that is the least likely type of structure that would contain oil or gas. The proposed deep, multipurpose borehole drilled in a synclinal position or offstructure location within or near the controlled area study zone would greatly enhance a comparison of the controlled area study zone to an analog for the hydrocarbon resource potential evaluation.

Hydrocarbon resource potential task--This task will involve the mapping of an area of the Columbia Plateau, including the Hanford Site, to identify hydrocarbon prospects. Structural and stratigraphic contour maps will be compiled, augmented by geologic and seismic interpretations of surface and subsurface data. A comprehensive interpretation will identify prospects that may be likely candidates for hydrocarbon exploration. This task will provide a relative comparison of hydrocarbon resource potential within the controlled area study zone to potential in the surrounding geologic setting.

Present day resource value analysis--For this analysis each identified prospect will be evaluated for estimated potential reserves and commercial production rate. The results from this analysis will provide input to performance assessment to determine the probability for human intrusion into the repository during future exploration or exploitation of natural resources.

8.3.1.6.3.3.3 Geothermal resources component.

Geothermal resources have not been used to any significant extent within 100 km (62 mi) of the Hanford Site, except for one artesian well (33 °C) near Yakima, Washington. Geothermal resource potential assessments have been made of the following areas (see also Sections 1.3.2.5.2.4 and 1.7): Washington State (Blackwell, 1974), Pasco Basin and vicinity (Murphy and Johnpeer, 1981; GG/GLA, 1981), Moses Lake-Ritzville-Connell, Washington (an area just northeast of the Hanford Site) (Widness, 1983), Columbia Basin Province (BLM, 1986), and Washington, Oregon, Idaho, and Montana (Washington State Energy Office, 1985).

All of these evaluations indicate there is low probability that high-temperature geothermal resources occur at shallow depths (less than 914.4 m (3,000 ft)) within the Columbia Plateau. The BLM (1986) evaluation suggests there may be moderate to low-temperature geothermal resources in the Columbia Basin Province. The evaluations of Murphy and Johnpeer (1981), GG/GLA (1981), Widness (1983), and the Washington State Energy Office (1985) suggest a potential for the occurrence of low-temperature geothermal water at certain sites in the Columbia Plateau. These studies did not include temperature data from the deep wells. Such potential has not been precisely evaluated for the Hanford Site, and the potential commercial value is presently unknown for the Hanford Site.

The tasks, tests, and analyses identified with this component are listed in Table 8.3.1.6-2 and described below.

Information compilation task--The objective of this task is to update resource information, as necessary, with newly published reports, evaluations, or studies on geothermal resources in the region. This includes leasing or exploration activity and the drilling of boreholes for heatflow, geothermal, or temperature surveys. Previous surveys and studies have been identified in the literature published by the Federal, state, and county governments, as well as studies by consultants to the BWIP.

Monitoring task--The objective of this task is to monitor ongoing geothermal exploration and development activity surrounding the site and within the Columbia Plateau. Maps will be used to show the location of drilling and testing of wells, geologic or geophysical surveys, or leasing.

Temperature analysis--This analysis will use published reports and surveys on temperature data and temperature measurements taken in boreholes within the Hanford Site. The temperature data measurements will be plotted on a map by borehole location with the depth at which the measurement was taken. The method used for taking the temperature measurement will be noted and evaluated. In addition, temperature logs and bottom hole temperature data (measurements corrected for time since drilling to get equilibrium temperature) from the deep wells will be used. This analysis will yield a thermal map for the Hanford Site and an evaluation of the data base. Temperature surveys outside of the Hanford Site will be used to supplement the Hanford Site data base map.

Thermal conductivity measurement test--This test will use cuttings from the sub-basalt sedimentary section of the deep wells and samples from the basalt margin geology stratigraphic units that trend beneath the basalts. A thermal conductivity test determines the ability of a material to conduct heat. In addition, a selected set of representative basalt samples will be tested by the same laboratory to establish a complete suite of thermal conductivity measurements for the stratigraphic section at the Hanford Site.

Heat flow analysis--This analysis will use the temperature data and the thermal conductivity measurements to determine heat flow for the Hanford Site. In addition, published heat flow measurements will supplement the established data base to produce a heat flow map for the Hanford Site that extends into the Columbia Plateau.

Geothermal potential analysis--This analysis will use the heat flow analysis map, the surface structure map (compiled and completed by the BWIP), and geophysical surveys (e.g., magnetotelluric, gravity, magnetic, etc.) to identify any trends of heat flow and structure. This information will be used in identifying areas for potential geothermal resources.

Analog comparison task--This task will compare the controlled area study zone to an analog area on the Columbia Plateau for geothermal resource potential.

Present day resource value analysis--For this analysis each area that has been identified by the temperature analysis as having potential as a geothermal resource will be evaluated using the Georank system developed and published for The Bonneville Power Administration by the Washington State Energy Office (1985). The results from this analysis will provide input to performance assessment to determine the probability for human intrusion into the repository during future exploration or exploitation of geothermal resources.

8.3.1.6.3.4 Application of results

All items of information produced by this investigation will be used in evaluating the mineral, hydrocarbon, and geothermal resource potential of the Hanford Site. The results from this investigation will be used as input to performance assessment evaluations of human interference scenarios.

Several individual tasks within this investigation support other investigations. Analyses of geophysical data, deep well logs, and basalt margin geology will support structural model development (Section 8.3.1.2.3). Sampling and isotopic analysis of gas from the Rattlesnake Hills gas field will support the hydrochemical characterization investigation (Section 8.3.1.4.3).

8.3.1.6.3.5 Schedule and milestones

Major milestones and expected delivery dates for the investigation are shown in Table 8.3.1.6-4. The estimated schedule of the study is shown in Figure 8.3.1.6-5.

8.3.1.6.4 Investigation of water resource potential

Water resources in the Columbia Plateau include surface water (primarily rivers) and groundwater. Future development of water resources could alter vertical and (or) horizontal hydraulic gradients. Such changes in gradient potentially could alter groundwater flow patterns in the controlled area study zone, thereby affecting repository performance.

Impacts of water resource development that may alter hydraulic gradients fall into two general categories: (1) decreased hydraulic head from groundwater withdrawal and (2) increased hydraulic head from induced recharge. Activities resulting in decreased head include the following:

- Groundwater withdrawal within the Hanford Site.

Increased pumping of existing water supply wells and (or) construction of new wells within the Hanford Site can shorten flow paths or decrease travel time by breaching confining layers or by increasing vertical or horizontal gradients.

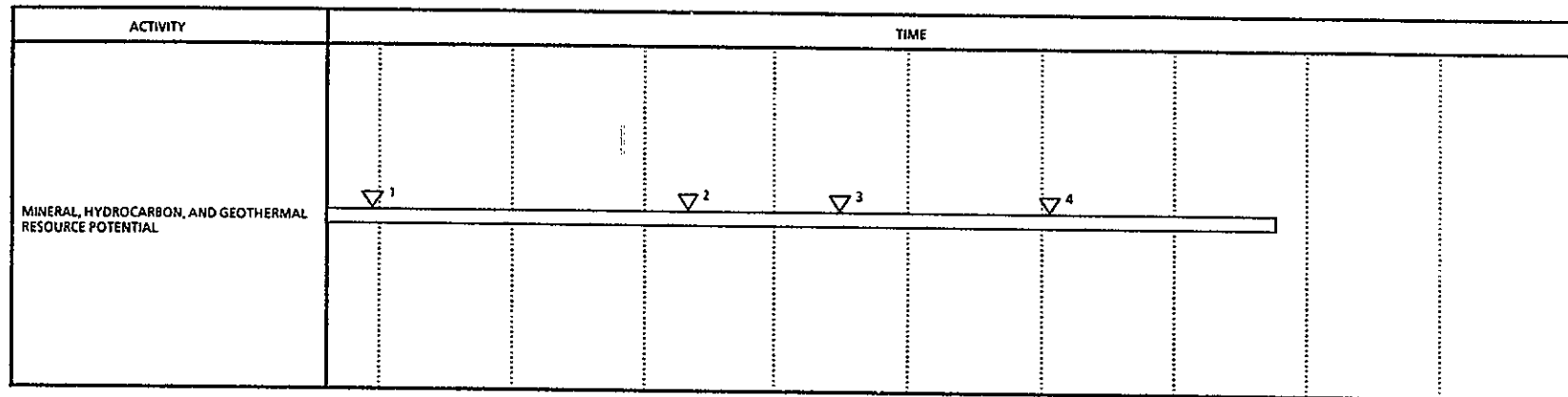
- Groundwater irrigation.

Groundwater is used for agricultural irrigation in many areas of the Columbia Plateau. Water level declines associated with groundwater irrigation have been observed in some locations (see Section 3.8).

Table 8.3.1.6-4. Major milestones and expected delivery dates of mineral, hydrocarbon, and geothermal resource potential investigation

Milestone	Date
Deep borehole position paper	December 1987
Mineral resource potential assessment	May 1989
Geothermal resource potential assessment	August 1990
Hydrocarbon resource potential assessment	January 1992
Analog comparison	April 1992
Economic evaluation	April 1992

PST87-2005-8.3.1.6-3



PSM-2014-8.3.1.6-1

- ▽¹ DEEP BOREHOLE POSITION PAPER.
- ▽² MINERAL RESOURCE POTENTIAL ASSESSMENT; FINAL DATA BASE COMPLETE;
ASSESSMENT USED IN PERFORMANCE ASSESSMENT.
- ▽³ GEOTHERMAL RESOURCE POTENTIAL ASSESSMENT; FINAL DATA BASE COMPLETE;
ASSESSMENT USED IN PERFORMANCE ASSESSMENT.
- ▽⁴ HYDROCARBON RESOURCE POTENTIAL ASSESSMENT; FINAL DATA BASE COMPLETE;
ASSESSMENT USED IN PERFORMANCE ASSESSMENT.

Figure 8.3.1.6-5. Mineral, hydrocarbon, and geothermal resource potential investigation schedule.

- Municipal, domestic, and industrial groundwater supply.

Groundwater withdrawal for municipal and industrial water supply can decrease water levels and alter hydraulic gradients in a manner similar to groundwater irrigation. Municipal and domestic sources of drinking water are included as special sources of groundwater addressed in Issue 1.3. The water resource potential study will compare the fixed and variable costs of developing surface water, shallow well, and deep well sources of drinking water within the controlled area study zone.

Water resource activities resulting in increased head include the following:

- Surface water irrigation.

In areas where surface water is abundant, it commonly is used for irrigation. Irrigation in excess of crop needs can percolate to the water table. Eventually, water levels may increase both in unconfined and in confined aquifers (see Section 3.8).

- Impoundments associated with dams.

Impoundments behind dams can alter hydraulic gradients by inducing recharge to underlying aquifers in a manner similar to surface water irrigation. A dam has been proposed for the Hanford Reach of the Columbia River (Ben Franklin Dam). Harty (1979, p. 31) predicts an associated water level rise of approximately 3 m (10 ft) in the unconfined aquifer in the vicinity of the controlled area study zone (see Section 3.8).

- Liquid waste disposal.

Disposal of liquid wastes in ponds and lagoons can induce water level rises in underlying aquifers. This phenomenon is similar to the effect of impoundments but on a smaller scale. Injection of liquid waste into aquifers can alter head directly. An additional impact of liquid waste disposal is degradation of groundwater quality.

Water resource demand in the Pasco Basin is likely to increase in the future for agricultural, industrial, and municipal purposes (Leaming, 1981, pp. 20-21). Water resource potential must be investigated to assess the likely impacts of this increased development in the future.

8.3.1.6.4.1 Purpose and objectives

The purpose of this water resource potential investigation is to assess how future activities involving water resources will alter regional groundwater flow and hydrologic boundary conditions of the controlled area study zone. Objectives of this investigation are the following:

1. Identification of past, present, and potential water resource activities.
2. Analysis of sensitivity of the groundwater system to changes in water resource activities.
3. Analysis of sensitivity of the groundwater system to changes in water resource development scenarios (i.e., multiple water resource activities).

Additional modeling will be necessary if objective 3 indicates that future water resource development may alter groundwater flow patterns significantly in the vicinity of the controlled area study zone. A hydrologic model at the scale of the controlled area study zone is planned as part of the site groundwater study (see Section 8.3.1.3 and the Site Groundwater Study Plan (Hiergesell, 1987)). Performance assessment modeling also may be required to evaluate the impacts of water resource development on the long-term performance of the repository.

8.3.1.6.4.2 Rationale

The water resource potential investigation addresses the need for understanding whether or not future development of water resources could affect repository performance. The investigation will assess the impacts of water resource development on a regional (Pasco Basin or larger) scale by means of numerical simulations. The results of this investigation will provide boundary conditions for additional modeling of a smaller area (i.e., the controlled area study zone or the repository).

One of the objectives of this investigation is to identify future water resource development that could potentially impact groundwater flow patterns in the controlled area study zone. To meet this objective, information will be gathered from an evaluation of past and present water resource activities, future climate data, water quality records, and present and anticipated water regulatory requirements. The resultant evaluation will be used to quantify hydrologic parameters to input to a regional groundwater flow model. This model will be used to analyze the sensitivity of the groundwater flow system to individual and multiple water resource activities.

8.3.1.6.4.3 Description of study

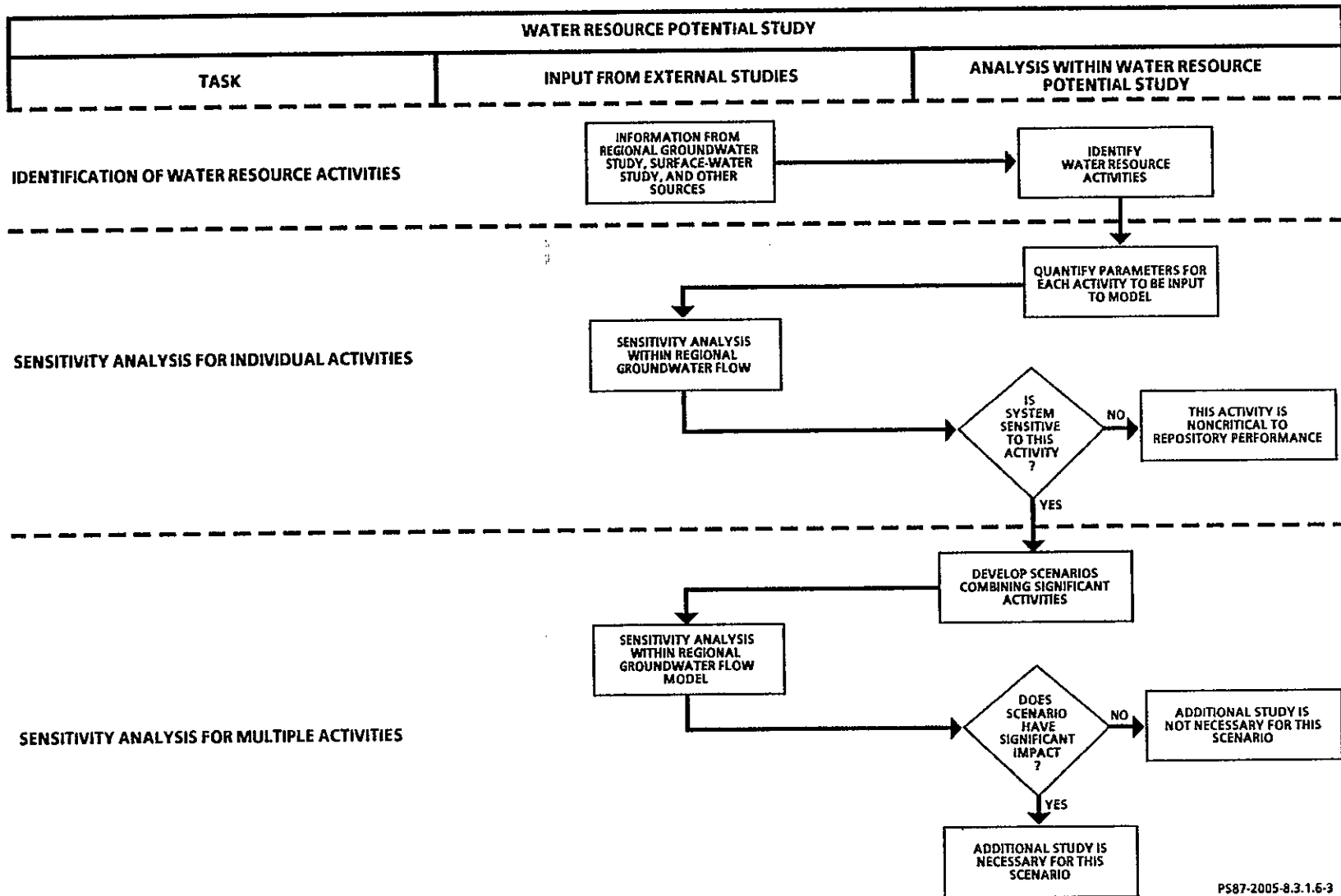
This investigation is comprised of a single study that addresses the potential for development of surface water and groundwater resources in the Columbia Plateau. Numerical modeling for the Water Resource Potential Study Plan (Roley, 1987b) will be conducted in conjunction with the regional groundwater study (see Section 8.3.1.3.4.3.1 and Regional Groundwater Study Plan (Roley, 1987a)). The interaction between the two studies is illustrated in Figure 8.3.1.6-6. The water resource potential study is divided into three major tasks: (1) identification of water resource activities, (2) sensitivity analysis for individual activities, and (3) sensitivity analysis for multiple activities. A detailed description of the study is presented in Roley (1987a).

The ability to assess the impacts of future development projects on groundwater flow is limited by the accuracy of long-term predictions. This study will address shorter term predictions (i.e., preclosure) in more detail than long-term predictions. Projections for the very distant future may be simplified to "worst-case" conditions (i.e., reasonably anticipated scenarios that would have the most significant impacts on hydraulic gradients).

8.3.1.6.4.3.1 Identification of water resource activities.

A water resource activity is any anthropogenic activity that significantly affects groundwater or surface water resources. Examples of water resource activities in the Columbia Plateau include groundwater irrigation, surface water irrigation, municipal or industrial wells, and impoundments, as discussed in Section 8.3.1.6.4. Information on past and present water resource activities in the Columbia Plateau will be obtained from other BWIP studies (e.g., regional groundwater and surface water system studies, Section 8.3.1.3). This information will be used to identify potential future water resource activities. Water resource programs currently in the planning stages will be discussed with responsible managing agencies. These programs will form the baseline for future water resource activities. Areas where future development is not currently planned but that show a potential for future water resource utilization will also be assessed.

A number of factors will determine the level and type of water resource development in the future (Table 8.3.1.6-5). These factors must be considered in identifying significant water resource activities. Water resource economics is one key factor in water resource development. For example, the likelihood of pumping from the Grande Ronde Basalt depends on the cost of high pumping lifts (approximately 750 m (2,500 ft) in the central Pasco Basin) versus the supply and demand of water. Socioeconomic projections entail a number of supporting parameters, including population projections, projected cropland distribution, availability of surface water, and future energy demand.



PS87-2005-8.3.1.6-3

Figure 8.3.1.6-6. Organization of water resource potential study.

Table 8.3.1.6-5. Factors influencing water resource development

Type of water use	Potential impacts on groundwater	Factors determining level of development
Groundwater withdrawal within the Hanford Site	Breach confining layers; decrease hydraulic head	Water resource economics; regulatory requirements
Groundwater irrigation	Decrease hydraulic head	Water resource economics, agricultural economics, regulatory requirements
Municipal/domestic and industrial groundwater supply	Decrease hydraulic head	Water quality, water resource economics, demographics, regulatory requirements
Surface-water irrigation	Locally increase loading on underlying aquifers; increase hydraulic head	Water resource economics, agricultural economics, regulatory requirements
Impoundments associated with dams	Locally increase loading on underlying aquifers; increase hydraulic head	Energy economics, demographics, regulatory requirements
Liquid waste disposal (ponds and injection)	Increase hydraulic head; change groundwater water quality	Industrial and municipal waste production and disposal practices; demographics, regulatory requirements

PST87-2005-8.3.1.6-4

Future climate may influence water resource economics and therefore affect future water supply. For example, a major increase in precipitation could elevate the water table, increasing the amount of water available from the unconfined aquifer. Conversely, a decrease in precipitation could necessitate the development of water resources that are currently undeveloped. Estimates of future climate conditions will be input to the Water Resource Potential Study Plan (Roley, 1987b) from the Future Climatic Change Study Plan (Underberg, 1987) (see Section 8.3.1.5.4.3).

Water quality also plays a role in resource development. For example, the high fluoride content of water drawn from the Grande Ronde Basalt in the Pasco Basin makes it unacceptable for municipal or domestic use without treatment. However, it may be a potential water source for industrial or agricultural purposes.

Regulatory requirements exert another influence on future water resource development. New development may be limited by water rights laws, water quality criteria, etc.

8.3.1.6.4.3.2 Sensitivity analysis for individual activities.

Hydrologic parameters will be quantified for the identified water resource activities. These parameters will be input to the regional groundwater flow model (see Section 8.3.1.3.4.3.1 and Roley (1987a)). The parameters will be varied to assess the sensitivity of the groundwater flow system to changes in water resource activities. Screening criteria will be developed to define what constitutes a "significant" change in the groundwater

flow system. It is possible that individual activities not producing significant changes may produce significant changes when combined with other activities. The possibility of such impacts will be considered in development of screening criteria. The results of this task will be input to the following task, sensitivity analysis for multiple activities.

8.3.1.6.4.3 Sensitivity analysis for multiple activities.

A range of possible water development scenarios will be produced combining water resource activities that impact the groundwater flow system significantly. The scenarios will incorporate multiple water resources projects staged over time to address a wide range of potential conditions. The impacts of these scenarios on hydraulic head at the boundary of the controlled area study zone will be evaluated using the regional groundwater flow model. Screening criteria will be developed to identify those scenarios that may affect repository performance adversely (i.e., by increasing hydraulic gradients). These scenarios will require further study (e.g., site-scale modeling (see Section 8.3.1.3.4.3.2) or performance assessment modeling (see Section 8.3.5.2)).

8.3.1.6.4.4 Application of results

Results of this study will include a set of critical water resource development scenarios for both individual and multiple activities that may occur in the future. These scenarios will be applied to the regional groundwater flow model (Section 8.3.1.3.4.3.1), which will predict possible adverse boundary conditions applied to site-scale modeling (Section 8.3.1.3.4.3.2). Economic evaluation of the development of drinking water supplies within the controlled area study zone will be used to address Issue 1.3.

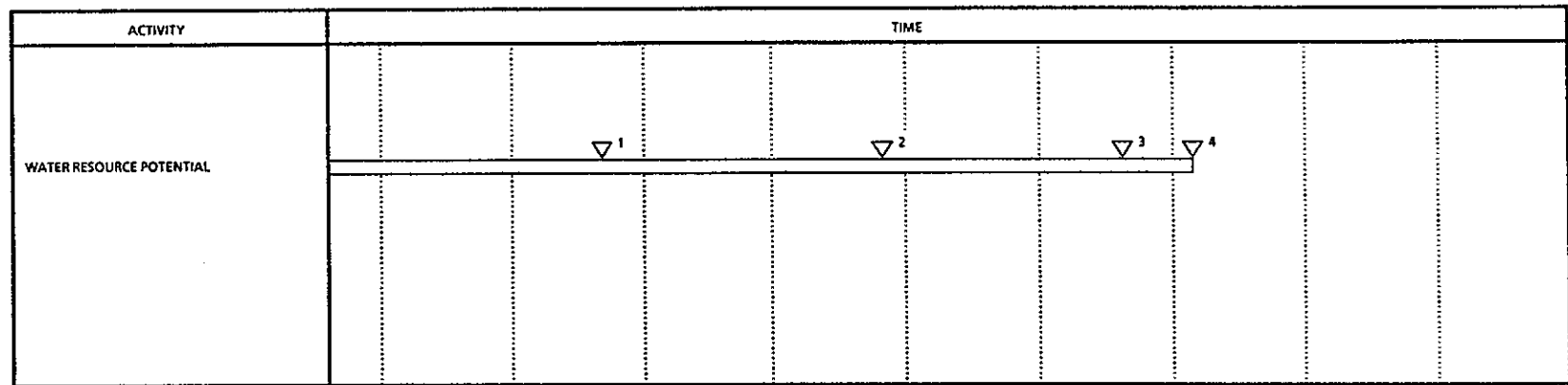
8.3.1.6.4.5 Schedule and milestones

Major milestones and expected delivery dates of the groundwater resource potential study are summarized in Table 8.3.1.6-6. The estimated schedule of the study is shown in Figure 8.3.1.6-7.

Table 8.3.1.6-6. Major milestones and expected delivery dates for water resource potential investigation

Milestone	Date
Identify water resource activities	September 1989
Sensitivity analysis for individual water resource activities	November 1990
Sensitivity analysis for multiple water resource activities (scenarios)	August 1992

PST87-2005-8.3.1.6-5



PS40-2014-0.2.1.6-2

- ▽¹ IDENTIFICATION OF ALTERNATIVE DEVELOPMENT PROJECTS NEEDED FOR ISSUES 1.3 AND 1.8.
- ▽² EVALUATION OF RESULTS FROM SINGLE PROJECT SCENARIO MODELING SENSITIVITY ANALYSIS PERFORMED USING REGIONAL GROUNDWATER MODEL FOR PASCO BASIN.
- ▽³ EVALUATION OF RESULTS FROM MULTIPLE PROJECT SCENARIO MODELING.
- ▽⁴ ANALYSIS OF BOTH SINGLE AND MULTIPLE PROJECT SCENARIOS ON CONTROLLED AREA STUDY ZONE BOUNDARY CONDITIONS TO CLOSE ISSUE 1.8.

Figure 8.3.1.6-7. Water resource potential investigation schedule.

8.3.1.6.5 References

- Blackwell, D. D., 1974. Terrestrial Heat Flow and its Location of Geothermal Reservoirs in Washington, Information Circular No. 50, State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, pp. 21-33. [MF 3142]
- BLM, 1986. Five Year Mineral Programs Forecast, BLM-OR-PT-86-005-4113, U.S. Department of the Interior, Bureau of Land Management, Portland, Oregon. [MF 3639]
- Campbell, N. P., 1985. Stratigraphy and Hydrocarbon Potential of the Northwestern Columbia Basin Based on Recent Drilling Activities, SD-BWI-TI-265, Rockwell Hanford Operations, Richland, Washington. [MF 2075]
- DOE, 1987. General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories, Title 10, Code of Federal Regulations, Part 960, U.S. Department of Energy, Washington, D.C. [MF 4849]
- EPA, 1986.* Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, D.C. [MF 4906]
- Fecht, K. R., S. P. Reidel, and A. M. Tallman, 1984. Paleodrainage of the Columbia River System on the Columbia Plateau of Washington State: A Summary, RHO-BW-SA-318 P, Rockwell Hanford Operations, Richland, Washington. [MF 2166]
- GG/GLA, 1981. Economic Geology of the Pasco Basin, Washington and Vicinity, RHO-BWI-C-109, Geosciences Group and George Leaming Associates for Rockwell Hanford Operations, Richland, Washington. [MF 0064]
- Harty, H., 1979. The Effects of the Ben Franklin Dam on the Hanford Site, PNBL-2821, Pacific Northwest Laboratory, Richland, Washington. [MF 1394]
- Hiergesell, R. A., 1987. Site Groundwater Study Plan, SD-BWI-SP-057, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Landon, R. D., 1987. Stratigraphy Study Plan, SD-BWI-SP-035, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Leaming, G. F., 1981. An Evaluation of Water-Resource Economics Within the Pasco Basin, Washington, RHO-BWI-C-121, George Leaming Associates for Rockwell Hanford Operations, Richland, Washington. [MF 0050]

*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Sub-part B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

- Lingley, W. S. Jr., and T. J. Walsh, 1986. "Issues Relating to Petroleum Drilling Near the Proposed High-Level Nuclear Waste Repository at Hanford," Washington Geologic Newsletter, Vol. 14, No. 3. [MF 0667]
- Myers, C. W., and S. M. Price (eds.), 1981. "Bedrock Structure of the Cold Creek Syncline Area," Subsurface Geology of the Cold Creek Syncline, RHO-BWI-ST-14, Rockwell Hanford Operations, Richland, Washington, Chapter 8, pp. 8-1 to 8-23. [MF 0067]
- Moses, L. J., 1987. Mineral, Hydrocarbon, and Geothermal Resource Potential Study Plan, SD-BWI-SP-044, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Murphy, P. J., and G. D. Johnpeer, 1981. An Assessment of Geothermal Resource Potential, Pasco Basin and Vicinity, Washington, RHO-BW-CR-128 P, Ertec Western, Inc., for Rockwell Hanford Operations, Richland, Washington. [MF 1046]
- NRC, 1987. Disposal of High-Level Radioactive Wastes in Geologic Repositories: Licensing Procedures, Title 10, Code of Federal Regulations, Part 60, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4903]
- Roley, K. L., 1987a. Regional Groundwater Study Plan, SD-BWI-SP-053, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Roley, K. L., 1987b. Water Resource Potential Study Plan, SD-BWI-SP-051, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Underberg, G. L., 1987. Future Climatic Change Study Plan, SD-BWI-SP-049 Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Washington State Energy Office, 1985. Evaluation and Ranking of Geothermal Resources for Electrical Generation or Electrical Offsets in Idaho, Montana, Oregon, and Washington, DOE/BP/13609--3, DE85 014661, Washington State Energy Office for Bonneville Power Administration, Portland, Oregon. [MF 3644]
- Widness, S., 1983. Low Temperature Geothermal Resource Evaluation of the Moses Lake-Ritzville-Connell Area, Washington, Open-File Report 83-11, Washington Department of Natural Resources, Olympia, Washington, p. 27. [MF 4191]

SITE CHARACTERIZATION PLAN

Chapter 8 - SITE CHARACTERIZATION PROGRAM

Section 8.3.2

Repository Program

9 2 1 2 5 5 5 0 3 7 5

9 2 1 2 5 5 0 3 7 6

THIS PAGE
INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
8.3.2 Repository Program	8.3.2-1
8.3.2.1 Overview	8.3.2.1-1
8.3.2.1.1 Requirements governing the repository program	8.3.2.1-1
8.3.2.1.2 Issues and issue resolution strategies guiding the repository program	8.3.2.1-4
8.3.2.1.3 Approach to investigations	8.3.2.1-6
8.3.2.1.4 Organization of Section 8.3.2	8.3.2.1-7
8.3.2.2 Specific program to verify or measure host rock environment	8.3.2.2-1
8.3.2.2.1 Purpose and objectives	8.3.2.2-1
8.3.2.2.2 Rationale	8.3.2.2-3
8.3.2.2.2.1 Technical background	8.3.2.2-13
8.3.2.2.2.2 Constraints	8.3.2.2-18
8.3.2.2.3 Description of studies	8.3.2.2-21
8.3.2.2.3.1 In situ stress determination study	8.3.2.2-21
8.3.2.2.3.2 Thermal properties determination study	8.3.2.2-29
8.3.2.2.3.3 Mechanical properties study	8.3.2.2-34
8.3.2.2.3.4 Opening performance study	8.3.2.2-44
8.3.2.2.4 Application of results	8.3.2.2-50
8.3.2.2.5 Schedule and milestones	8.3.2.2-52
8.3.2.3 Specific program for coupled interaction tests	8.3.2.3-1
8.3.2.4 Specific program for design optimization	8.3.2.4-1
8.3.2.4.1 Purpose and objectives	8.3.2.4-13
8.3.2.4.2 Rationale	8.3.2.4-14
8.3.2.4.2.1 Surface facilities	8.3.2.4-14
8.3.2.4.2.2 Underground facilities	8.3.2.4-14
8.3.2.4.2.3 Design analyses	8.3.2.4-14
8.3.2.4.3 Description of activities	8.3.2.4-16
8.3.2.4.3.1 Waste package design alternatives	8.3.2.4-18
8.3.2.4.3.2 Waste package underground location design alternatives	8.3.2.4-18
8.3.2.4.3.3 Waste package emplacement system design alternatives	8.3.2.4-24
8.3.2.4.3.4 Repository layout alternatives	8.3.2.4-25
8.3.2.4.3.5 Access shafts design alternatives	8.3.2.4-26
8.3.2.4.4 Application of results	8.3.2.4-27
8.3.2.4.5 Schedule and milestones	8.3.2.4-30
8.3.2.5 Specific program for repository modeling	8.3.2.5-1
8.3.2.5.1 Purpose and objectives	8.3.2.5-3

TABLE OF CONTENTS (Continued)

	<u>Page</u>
8.3.2.5.2 Rationale	8.3.2.5-4
8.3.2.5.2.1 Analysis techniques	8.3.2.5-9
8.3.2.5.2.2 Code verification	8.3.2.5-10
8.3.2.5.2.3 Model validation	8.3.2.5-11
8.3.2.5.3 Investigation of repository geomechanics models	8.3.2.5-13
8.3.2.5.3.1 Purpose and objectives	8.3.2.5-13
8.3.2.5.3.2 Rationale	8.3.2.5-14
8.3.2.5.3.3 Description of studies and activities	8.3.2.5-15
8.3.2.5.3.4 Application of results	8.3.2.5-21
8.3.2.5.3.5 Schedule and milestones	8.3.2.5-21
8.3.2.5.4 Investigation of additional repository design models	8.3.2.5-23
8.3.2.5.4.1 Purpose and objectives	8.3.2.5-23
8.3.2.5.4.2 Rationale	8.3.2.5-23
8.3.2.5.4.3 Description of activities	8.3.2.5-24
8.3.2.5.4.4 Application of results	8.3.2.5-29
8.3.2.5.4.5 Schedule and milestones	8.3.2.5-29
8.3.2.6 Specific program for waste retrieval	8.3.2.6-1
8.3.2.6.1 Purpose and objectives	8.3.2.6-4
8.3.2.6.2 Rationale	8.3.2.6-5
8.3.2.6.3 Description of activities	8.3.2.6-6
8.3.2.6.3.1 Compilation of retrievability strategy report	8.3.2.6-6
8.3.2.6.3.2 Development and demonstration of retrieval equipment	8.3.2.6-10
8.3.2.6.4 Application of results	8.3.2.6-11
8.3.2.6.5 Schedules and milestones	8.3.2.6-12
8.3.2.7 Specific design program for radiological health and safety	8.3.2.7-1
8.3.2.7.1 Purpose and objectives	8.3.2.7-3
8.3.2.7.2 Rationale	8.3.2.7-3
8.3.2.7.3 Investigation of normal operational radiological protection	8.3.2.7-4
8.3.2.7.3.1 Purpose and objectives	8.3.2.7-4
8.3.2.7.3.2 Rationale	8.3.2.7-5
8.3.2.7.3.3 Description of activities	8.3.2.7-5
8.3.2.7.3.4 Application of results	8.3.2.7-9
8.3.2.7.3.5 Schedule and milestones	8.3.2.7-11
8.3.2.7.4 Investigation of accident conditions for radiological protection	8.3.2.7-11
8.3.2.7.4.1 Purpose and objectives	8.3.2.7-11
8.3.2.7.4.2 Rationale	8.3.2.7-11
8.3.2.7.4.3 Description of activities	8.3.2.7-11

TABLE OF CONTENTS (Continued)

	<u>Page</u>
8.3.2.7.4.4 Application of results	8.3.2.7-12
8.3.2.7.4.5 Schedule and milestones	8.3.2.7-12
8.3.2.7.5 Investigation of radiological monitoring systems	8.3.2.7-13
8.3.2.7.5.1 Purpose and objectives	8.3.2.7-13
8.3.2.7.5.2 Rationale	8.3.2.7-13
8.3.2.7.5.3 Description of activities	8.3.2.7-13
8.3.2.7.5.4 Application of results	8.3.2.7-15
8.3.2.7.5.5 Schedule and milestones	8.3.2.7-15
8.3.2.8 Specific program for nonradiological health and safety of workers	8.3.2.8-1
8.3.2.8.1 Purpose and objectives	8.3.2.8-4
8.3.2.8.2 Rationale	8.3.2.8-4
8.3.2.8.3 Description of studies and activities	8.3.2.8-5
8.3.2.8.3.1 Compilation of applicable nonradiological health and safety requirements	8.3.2.8-6
8.3.2.8.3.2 Application of nonradiological health and safety requirements to design activities	8.3.2.8-6
8.3.2.8.3.3 Development of site characterization data needs and specifications	8.3.2.8-6
8.3.2.8.3.4 Development of repository construction and operation safety program document	8.3.2.8-7
8.3.2.8.3.5 Constructibility study	8.3.2.8-7
8.3.2.8.4 Application of results	8.3.2.8-8
8.3.2.8.5 Schedule and milestones	8.3.2.8-8
8.3.2.9 References	8.3.2.9-1

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.2.1-1	Regulatory requirements for health and safety in repository design	8.3.2.1-3
8.3.2.2-1	Test identification process	8.3.2.2-4
8.3.2.2-2	Schedule for geomechanics studies to determine host rock environment	8.3.2.2-53
8.3.2.4-1	Technical documents used for design development and site characterization	8.3.2.4-3
8.3.2.4-2	Content of Design and Development Plan and supplemental documents	8.3.2.4-5
8.3.2.4-3	Design and development process using the Design and Development Plan and supplemental documents	8.3.2.4-7
8.3.2.4-4	Design methodology structure and titles	8.3.2.4-9
8.3.2.4-5	Repository design optimization sequence of design alternative activities	8.3.2.4-19
8.3.2.4-6	Waste package design alternatives	8.3.2.4-20
8.3.2.4-7	Waste package underground location design alternatives	8.3.2.4-21
8.3.2.4-8	Waste emplacement system design alternatives	8.3.2.4-22
8.3.2.4-9	Repository design dependencies impacting repository layout alternatives	8.3.2.4-23
8.3.2.4-10	Example design methodology sheet	8.3.2.4-29
8.3.2.4-11	Activities leading to design and construction of a repository	8.3.2.4-31
8.3.2.4-12	Schedule for repository design activities	8.3.2.4-32
8.3.2.5-1	Numerical model development and validation	8.3.2.5-5
8.3.2.5-2	Components of a repository geomechanics model	8.3.2.5-7
8.3.2.5-3	Schedule for repository model development	8.3.2.5-22
8.3.2.6-1	Schedule for waste retrieval proof-of-principle testing	8.3.2.6-13

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.2.1-1	Repository design issues and information needs	8.3.2.1-5
8.3.2.2-1	Geomechanics performance parameters from issue resolution strategy	8.3.2.2-2
8.3.2.2-2	Geomechanics parameters	8.3.2.2-5
8.3.2.2-3	Geomechanics supporting parameters	8.3.2.2-10
8.3.2.2-4	In situ stress tests, studies, and supporting analyses	8.3.2.2-22
8.3.2.2-5	Thermal properties tests, studies, and supporting analyses	8.3.2.2-30
8.3.2.2-6	Mechanical properties tests, studies, and supporting analyses	8.3.2.2-35
8.3.2.2-7	Opening performance tests, studies, and supporting analyses	8.3.2.2-45
8.3.2.3-1	Site characterization tests involving coupled interactions	8.3.2.3-2
8.3.2.4-1	Design methodology definitions and structure correlated to issues-related controlling questions	8.3.2.4-10
8.3.2.4-2	Design analysis data requirements	8.3.2.4-17
8.3.2.4-3	Site characterization data related to design and construction sensitivity	8.3.2.4-28
8.3.2.5-1	Surface facilities modeling requirements for design	8.3.2.5-25
8.3.2.5-2	Surface facilities operations modeling requirements	8.3.2.5-26
8.3.2.5-3	Surface facilities modeling requirements for systems evaluation	8.3.2.5-27
8.3.2.5-4	Underground facilities modeling requirements for design	8.3.2.5-30
8.3.2.5-5	Underground facilities operations modeling requirements	8.3.2.5-30

This page intentionally left blank.

9 2 1 2 5 5 0 3 3 2

8.3.2 REPOSITORY PROGRAM

This section summarizes the host rock environment test program and provides an overview of the research and development and engineering that are required to ensure that the repository is capable of satisfying applicable performance, safety, and design objectives. The investigations and studies that form the Basalt Waste Isolation Project (BWIP) program for geomechanical and coupled interaction testing, repository design optimization, and related analysis and modeling are described.

The repository program is composed of three types of activities--data acquisition, design and safety, and analysis. The data acquisition needed to verify or measure the host rock environment is addressed in Section 8.3.2.2, and coupled interaction tests are addressed in Section 8.3.2.3. The design and safety activities addressed in this section of the repository program (Section 8.3.2) are design optimization (8.3.2.4), waste retrieval (8.3.2.6), radiological health and safety (8.3.2.7), and nonradiological health and safety of workers (8.3.2.8). Analysis activities are addressed in the discussion of the specific program for repository modeling (8.3.2.5).

Corresponding discussions of shaft and borehole seals and waste package are found in Sections 8.3.3 and 8.3.4, respectively.

This page intentionally left blank.

9 2 1 2 5 5 5 0 3 3 4

8.3.2.1 Overview

The purpose of Section 8.3.2 is to describe the specific programs, investigations, studies, and activities that define site characterization and repository design requirements. Details for studies, tests, and analyses will be presented in study plans separate from the Site Characterization Plan (SCP).

In this overview the repository program is introduced by discussing the links to the regulatory requirements and issue resolution strategies. It also provides background and overview concepts for test development, design, and analysis. This overview is completed by a brief introduction to the supporting sections that follow. This overview includes the following:

- Requirements governing the repository program (Section 8.3.2.1.1).
- Issues and issue resolution strategies guiding the repository program (Section 8.3.2.1.2).
- Approach to investigations (Section 8.3.2.1.3).
- Organization of Section 8.3.2 (Section 8.3.2.1.4).

8.3.2.1.1 Requirements governing the repository program

The U.S. Nuclear Regulatory Commission (NRC) regulations for disposal of high-level radioactive wastes in geologic repositories are given in 10 CFR 60, (NRC, 1987a). Regulations for the repository performance and design are given in the following 10 CFR 60 sections:

<u>Section No.</u>	<u>Title</u>
60.111	Performance of the geologic repository operations area through permanent closure.
60.112	Overall system performance objective for the geologic repository after permanent closure.
60.113	Performance of particular barriers after permanent closure.
60.130	Scope of design criteria for the geologic repository operations area.
60.131	General design criteria for the geologic repository operations area.

<u>Section No.</u>	<u>Title</u>
60.132	Additional design criteria for surface facilities in the geologic repository operations area.
60.133	Additional design criteria for the underground facility.
60.137	General requirements for performance confirmation.

The Generic Technical Position on Design Information Needs in the Site Characterization Plan (NRC, 1985) addresses the type and the level of detail of design information needs to be included in the SCP. This guidance is followed in Chapter 6 and in this section. The applicable regulatory requirements for preclosure and postclosure from this technical position are illustrated in Figure 8.3.2.1-1.

The repository design concerns discussed in this NRC technical position (NRC, 1985) not only highlight aspects of the above 10 CFR 60 (NRC, 1987a) regulatory requirements but also include concerns on the design process, alternative design concepts for the SCP, and the identification of uncertainties in the site parameters.

Design is an iterative and developmental process with specific phased outputs established for a nuclear waste repository. The following four repository design outputs have been predetermined by the Mission Plan for Civilian Radioactive Waste Management Program (DOE, 1985b):

1. Conceptual design for the site characterization plans.
2. Advanced conceptual design.
3. License application design.
4. Final procurement and construction design.

The first of these four major outputs, the SCP conceptual design phase, ends with the submittal of this SCP. The SCP repository conceptual design report (KE/PB, 1987a) has been produced and is summarized in Chapter 6.

The second major output is advanced conceptual design. This will develop alternative design concepts for elements of the repository as a part of planned engineering tradeoff studies. The alternative design concept that best handles the 10 CFR 60 performance and design requirements is brought forward to the license application design where it is detailed.

The license application design output fulfills the 10 CFR 60 requirements. Those items necessary to demonstrate compliance with the design requirements and performance objectives of 10 CFR 60 and the license application requirements of 10 CFR 60.21 will be developed.

AREAS OF RESPONSIBILITIES	PRECLOSURE PERIOD		POSTCLOSURE PERIOD
	OPERATION	RETRIEVAL	CONTAINMENT/ISOLATION
<u>RADIOLOGICAL SAFETY</u>			<u>10 CFR 60/EPA STANDARD (NRC, 1987a)</u>
• GEOLOGIC REPOSITORY OPERATIONS AREA			• RELEASE TO ACCESSIBLE ENVIRONMENT SHALL BE LESS THAN THE LIMITS SPECIFIED BY EPA STANDARD
- RESTRICTED AREA NORMAL OPERATION	← 10 CFR 20 (NRC, 1987b) →		• WASTE PACKAGE TO MEET CONTAINMENT PERIOD OF NOT LESS THAN 300 YR NOT MORE THAN 1,000 YR
ACCIDENTS	← NO DIRECTLY APPLICABLE LIMIT →		
- UNRESTRICTED AREA NORMAL OPERATIONS	← EPA STANDARD (25 MREM/YR) →		• ENGINEERED BARRIER SYSTEM TO MEET 10^{-5} RELEASE RATE
	← 10 CFR 20 AND 10 CFR 60.111 →		• 1,000-YR GROUNDWATER TRAVEL TIME TO ACCESSIBLE ENVIRONMENT
ACCIDENTS	← 10 CFR 60.2 (500 MREM/EVENT) →		
• OTHER SUPPORTING REQUIREMENTS	← ENSURE ABILITY TO RETRIEVE 10 CFR 60.111(b) →		<u>SUPPORT FOR MEETING EPA STANDARD AND PERFORMANCE OBJECTIVES</u>
	← MAINTAIN STABLE OPENINGS 10 CFR 60.133(e) →		• MAINTAIN INTEGRITY OF THE WASTE PACKAGE
			• ENSURE CONSTRUCTION-RELATED EFFECTS (e.g., SUBSIDENCE, FRACTURING) DO NOT RESULT IN SIGNIFICANT TRANSPORT PATHWAYS
NONRADIOLOGICAL SAFETY (PROTECTION OF WORKERS FROM INJURY AND DEATH)	← CONCERNS COVERED IN MSHA (1987) AND OSHA (1986) regulations →		

*See 10 CFR for further details.

EPA = U.S. ENVIRONMENTAL PROTECTION AGENCY.
 MSHA = MINE SAFETY AND HEALTH ADMINISTRATION.
 OSHA = OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION

PS87-2005-8.3.2-3

Figure 8.3.2.1-1. Regulatory requirements for health and safety in repository design.

If the site is found acceptable and the license application is approved, the final procurement and construction design will proceed. During this final design effort, nonlicensing-related ancillary systems will be designed. Final design refinement for items necessary to demonstrate compliance with the design criteria and performance objectives of 10 CFR 60 (NRC, 1987a), development of construction bid packages for all systems, and development of final construction and procurement schedules will result in the production of contract documents for repository construction.

8.3.2.1.2 Issues and issue resolution strategies guiding the repository program

As explained in Section 8.1 the issues hierarchy consists of key issues plus the associated performance and design issues. The key issues embody the principal requirements established by the regulations governing geologic disposal. Each of the key issues is followed by issues that expand on the requirements of the key issue. Key Issue 1 contains postclosure performance requirements. Key Issue 2 contains preclosure radiological safety and retrievability requirements. Key Issue 3 is concerned with environmental, socioeconomic, and transportation impacts that do not depend directly on site characterization and, therefore, is not discussed further. Key Issue 4 is concerned with ease and cost of repository siting, construction, operation, and closure.

The Office of Geologic Repositories Issues Hierarchy for a Mined Geologic Disposal System (DOE, 1987c) is presented in Section 8.2.1.6 of this document. The issue resolution strategy developed for each of these performance and design issues is presented in Section 8.2.2. These strategies have identified performance measures, parameters, and information needs required to resolve the performance or design issues. The postclosure Issue 1.11 and the preclosure Issues 2.7 and 4.2 require a wide assortment of information needs as shown in Table 8.3.2.1-1.

The parameters from these performance and design issues that can be categorized as geomechanical have been sorted into the following information needs: in situ stress state, host rock mechanical properties, host rock thermal properties, and opening performance. In Section 8.3.2.2, these four information needs become the four studies discussed. These four studies are further justified by Issues 1.1, 1.4, 1.5, 1.8, 2.3, and 2.4; and Issues 1.10, 1.12, and 2.6 that require the same geomechanical information needs and related performance parameters.

Measurement of the parameters listed in Table 8.3.2.2-1 may be influenced by coupled phenomena or processes active in the test environment. Coupled phenomena occur when two or more of the following variables interact with one another: thermal, hydrological, geochemical, and mechanical effects.

Table 8.3.2.1-1. Repository design issues and information needs

Postclosure design issues	Preclosure design issues	Information needs	Corresponding Site Characterization section
1.11	2.7, 4.2	Stratigraphy (intraflow structure)	8.3.1.2.3.3.1
1.11	2.7, 4.2	Cooling joint characteristics	8.3.1.2.3.3.3
1.11	2.7, 4.2	Structural geology	8.3.1.2.3.3.4
1.11	2.7, 4.2	Physical rock properties	8.3.1.2.3.3.5
1.11	2.7, 4.2	Seismology	8.3.1.2.4.3.2
	2.7, 4.2	Surface water system	8.3.1.3.3.3.1
	2.7, 4.2	Surface site characteristics	*
	2.7, 4.2	Site flooding	8.3.1.3.3.3.2
1.11	2.7, 4.2	Site groundwater (subsurface hydrology)	8.3.1.3.4.3.2
1.11	2.7, 4.2	Groundwater flow system hydrochemistry	8.3.1.4.3.3.1
	2.7, 4.2	Meteorology (natural phenomena)	8.3.1.5.5.3
1.11	2.7, 4.2	In situ stress state	8.3.2.2.3.1
1.11	2.7, 4.2	Host rock thermal properties	8.3.2.2.3.2
1.11	2.7, 4.2	Host rock mechanical properties	8.3.2.2.3.3
1.11	2.7, 4.2	Opening performance	8.3.2.2.3.4
	2.7, 4.2	Constructibility	8.3.2.8.3.5

*The surface site characteristics are discussed in a portion of Sections 8.3.1.2.3.3.1, 8.3.1.3.3.3.1, 8.3.1.3.3.3.2, and 8.3.2.8.3.5.

PST87-2005-8.3.2-11

Coupled processes are not considered to be a discrete subset of the information needs identified in the issue resolution strategies but are part of the basic information required for an understanding of the in situ rock mass behavior. The linkage between coupled phenomena and site characterization tests is identified in Section 8.3.2.3.

Section 8.3.2.4, design optimization, is linked to the concerns and issue resolution strategies for Issue 1.11 on repository postclosure design; Issue 2.4 on retrievability; Issue 2.7 on repository preclosure design; Issue 4.2 on nonradiological worker safety; Issue 4.4 on adequacy of technology; and Issue 4.5 on costs. The concern of postclosure performance assessment from Issue 1.11 is a major aspect of design optimization.

Section 8.3.2.5, repository modeling, is linked to the analytical tools and modeling discussed in the issue resolution strategies from Issues 1.11, 2.4, 2.7, 4.2, 4.4, and 4.5.

Section 8.3.2.6, waste retrieval, is linked to the concerns and issue resolution strategy from Issue 2.4 on retrievability.

Section 8.3.2.7, radiological health and safety, is linked to the concerns and issue resolution strategies for Issue 2.1 on public safety during normal operations; Issue 2.2 on worker safety; Issue 2.3 on public safety during accidents; Issue 2.4 on retrievability; and Issue 2.7 on repository preclosure design. These safety aspects are the main preclosure performance concerns.

Section 8.3.2.8, nonradiological health and safety of workers, is linked to the concerns and issue resolution strategy from Issue 4.2.

8.3.2.1.3 Approach to investigations

Investigations included in the repository program are data acquisition and (or) testing investigations, design and safety investigations, and modeling investigations. The data acquisition investigation (geomechanics) is based on the performance parameters obtained by the issue resolution process from the design and performance issues. The design and safety investigations are derived mainly from the repository design and performance issues. The modeling investigations are based on the analysis needs of the geomechanics program and the design program.

The data acquisition, design, and analyses processes are not independent of each other. The data acquisition or testing program is dependent, in part, on the sensitivity of the design to the site characteristics data. A detailed definition of this sensitivity provides a basis for a data specification. Complete data specifications will address the quality assurance level, range, accuracy/tolerance, level of confidence, spatial/time dependencies, physical location, geometry, boundary conditions, test environment, operating conditions, priority, schedule, and other criteria for the data as appropriate.

From a well-structured data specification standpoint, and considering other relevant criteria, a plan of action for necessary tests can be developed in the study plans that includes identification of test concepts, test development logic, and the associated schedule. The tests are then designed and detailed test procedures developed. After the tests are conducted, the results are reviewed, evaluated, and reported for use in the applicable design or performance analysis. The study plans to obtain the geomechanics site data are identified in Section 8.3.2.2.

Because the design process has only been through the first phase of conceptual design (SCP conceptual design), much work remains to be done to optimize a repository design. As a tool to assist this process the Design Methodology document (KE/PB, 1987a) was created. The design methodology provides a guiding framework or structure that allows flexibility in developing design strategies to ensure that studies, tests, and experiments needed for design, licensing, and construction will be performed. The design process directed by the methodology identifies alternative methods of approach; guides possible design solutions by the use of tradeoff studies; provides traceability between information needs, specific design activities, and associated methods of construction; and serves as a "checklist" of the things that have to be done to obtain necessary and sufficient data to support the design. In the advanced conceptual design, the SCP conceptual design will be assessed by the tradeoff studies that have been identified in the Design Methodology document (KE/PB, 1987a). The results of these tradeoff studies are anticipated to significantly impact the present SCP design concepts. Details of these design development plans are provided in Section 8.3.2.4.

As the repository design progresses and design alternatives are evaluated, many of the repository modeling and analyses techniques or methods will be used. Use of these analysis methods will lead to the identification of any additional tests and studies necessary for evaluation of design alternatives. The modeling studies provide important information for studies other than design. For example, results from analyses that evaluate the effect of stress redistribution, construction and excavation techniques, and temperature change on the damaged rock surrounding waste package emplacement holes and repository openings must be considered by the seals and waste package groups. The necessity for additional testing can then be established on the basis of uncertainty in the available data and the sensitivity of the design to specific parameters. Discussion of the modeling activities necessary to determine this sensitivity is provided in Section 8.3.2.5.

8.3.2.1.4 Organization of Section 8.3.2

The individual sections of the repository program are presented in the same sequence as the annotated outline for SCPs (DOE, 1987a) with the additions indicated.

The specific program plans for geomechanical characterization of the host rock environment are described in Section 8.3.2.2. The single geomechanical investigation supporting this program has four subordinate studies--in situ stress determination, mechanical properties determination, thermal properties determination, and evaluation of opening performance. These four studies will be issued as study plans at the time this document is issued.

The specific program described in Section 8.3.2.3 relates coupled processes to the testing program identified in Section 8.3.2.2. Because investigation of coupled processes is an integral part of other site characterization studies, no specific studies of coupled processes are described in this subsection.

In Section 8.3.2.4, the BWIP's specific program to optimize the repository design to the site characteristics data found in the exploratory shaft facility testing program is described. As the advanced conceptual design and the required tradeoff studies are completed, the new design will be analyzed for its sensitivity to these site characteristics or parameters. The major alternatives that must be evaluated before a final design can be created are identified in the discussion for this section.

In Section 8.3.2.5 two repository modeling investigations are described: repository geomechanics analysis and additional repository design models. The design issue resolution strategies, discussed in Sections 8.2.2.1.11, 8.2.2.2.7, and 8.2.2.4.2, identify many types of analyses requiring the use of models. The design analyses activities described in this section are required to support the design process and, by determining the sensitivity of the models to site data or parameters, assist in determining data specifications.

Development of the repository design will require additional performance and safety emphasis in some areas of concern. To provide additional detail for specific design concerns from the issues hierarchy, sections are provided for waste retrieval (Section 8.3.2.6), radiological health and safety (Section 8.3.2.7), and nonradiological health and safety of workers (Section 8.3.2.8).

The waste retrieval program described in Section 8.3.2.6 consists of a single investigation supported by two subordinate activities: (1) the compilation of a retrievability strategy report, and (2) the development and demonstration of retrieval equipment development and demonstrations. The BWIP Retrievability Strategy Report will describe how the BWIP intends to conform to the Department of Energy Position on Retrievability and Retrieval for a Geologic Repository (DOE, 1985a). Proof-of-principle testing is the primary emphasis of the retrieval equipment development and demonstration activities.

The design program discussed in Section 8.3.2.7, radiological health and safety, includes the following three investigations: (1) normal operational radiological protection, (2) accident conditions for radiological protection, and (3) radiological monitoring systems. The engineering activities necessary to ensure that the repository can be designed, constructed, operated, and decommissioned in a manner that provides for radiological health and safety are described in this section.

The program for nonradiological health and safety of workers discussed in Section 8.3.2.8, describes plans to identify the needed occupational health and safety requirements, ensure they are used in the design process, and provide verification systems for design, construction, and operations. The program consists of a single investigation and the following four activities: (1) compilation of applicable nonradiological health and safety requirements, (2) application of nonradiological health and safety requirements to design activities, (3) development of site characterization data needs and specifications, and (4) development of the repository construction and operation safety program document. A constructibility study is also described. This study will define constructibility information related to nonradiological safety that will be obtained as the Exploratory Shaft Facility is constructed and operated.

9 2 1 2 5 5 5 0 3 9 3

This page intentionally left blank.

9 2 1 2 5 5 0 3 9 4

8.3.2.2 Specific program to verify or measure host rock environment

An in situ geotechnical testing program will be conducted during site characterization to obtain a geomechanical description of the repository host rock environment. This description of the host rock environment will be used in repository design and performance assessment. Plans for characterization of the host rock environment as it relates to design and performance of the repository subsystem are described in this section. This section is limited in scope to a discussion of the geomechanical characteristics of the host rock, although, in addition to geomechanical characteristics, the host rock environment consists of geologic, hydrologic, and geochemical, characteristics. Of these characteristics, geomechanics has the greatest impact on the design of the repository subsystem. However, all of these characteristics must be considered in the development of a site description as it relates to the repository.

Plans for geological characterization of the Hanford Site are presented in Section 8.3.1.2. Hydrologic and geochemical characterization plans are discussed in Sections 8.3.1.3 and 8.3.1.4, respectively. Coupled interactions, involving integration of several or all of these characteristics, are discussed in Section 8.3.2.3.

8.3.2.2.1 Purpose and objectives

This program is supported by a single investigation having a twofold purpose: (1) to measure those engineering parameters that describe the mechanical, thermal, and thermomechanical behavior of the repository host rock, which are necessary input for the numerical models used in design and performance assessment; and (2) to gather information used to validate the models with tests that simulate repository conditions.

The investigation will characterize the rock for three conditions: (1) preexcavation, (2) postsubsurface excavation/pre-waste-emplacement, and (3) post-waste-emplacement. Preexcavation condition is defined as the condition of the rock in its natural, undisturbed environment before the construction of any shafts or underground openings. Postsubsurface excavation/pre-waste-emplacement is defined as the condition of the rock after the creation of mined openings (both shafts and drifts) and before heating from waste emplacement. Post-waste-emplacement is defined as the condition of the rock after being subjected to elevated temperatures from waste-emplacement.

Under this investigation, the preexcavation host rock environment will be characterized by determining the natural state of stress, mechanical properties, and thermal properties of the host rock. To characterize the postexcavation/pre-waste-emplacement environment, excavation induced stresses will be determined and opening performance will be evaluated by monitoring prototypic openings and support systems and by measuring the properties of the

rock immediately surrounding these openings. To characterize the post-waste-emplacement environment, thermally induced stresses will be determined, and the thermomechanical response of the rock mass will be evaluated under conditions representative of those expected in a repository.

The site characterization testing program is based on determination of parameters needed for resolution of performance and design issues from the issues hierarchy as described in Section 8.2. To achieve the objectives of the investigation described in this section, parameters concerning the geo-mechanical performance characteristics of the host rock have been identified from several of the issues resolution strategies. Geomechanical performance parameters have been compiled in Table 8.3.2.2-1, which indicates the performance and design issues used to develop the parameter list. More detailed parameter lists are included in Section 8.3.2.2.2.

The information discussed above will be gathered under the following four studies:

1. In situ stress determination.
2. Thermal properties determination.
3. Mechanical properties determination.
4. Evaluation of opening performance.

Each study comprises a series of tests and analyses that will provide the required data. Identification of the tests and analyses to be included in the study is accomplished by a thorough review of the methods available for use, an evaluation of constraints, the ability to meet stated accuracy and quality requirements, and assessments of cost and schedule requirements. The tests currently identified to be included in the four studies listed above are described in Section 8.3.2.2.3. Once tests have been identified for inclusion in the study, a process of design and development is conducted to ensure that the tests will provide traceable, accurate data consistent with the

Table 8.3.2.2-1. Geomechanics performance parameters
from issue resolution strategy

Geomechanic performance parameters	Performance issues					Design issues					
	1.1	1.4	1.5	1.8	2.4	1.10	1.11	1.12	2.6	2.7	4.2
Total stress profile	X	X	X	X	X		X	X		X	X
Rock mass deformation*		X	X	X	X	X	X	X	X	X	X
Temperature distribution	X	X	X	X	X		X	X		X	X
Support system performance		X	X	X	X			X		X	X
Damaged rock zone	X	X	X	X	X		X	X		X	X

*includes creep.

PST87-2005-8.3.2-12

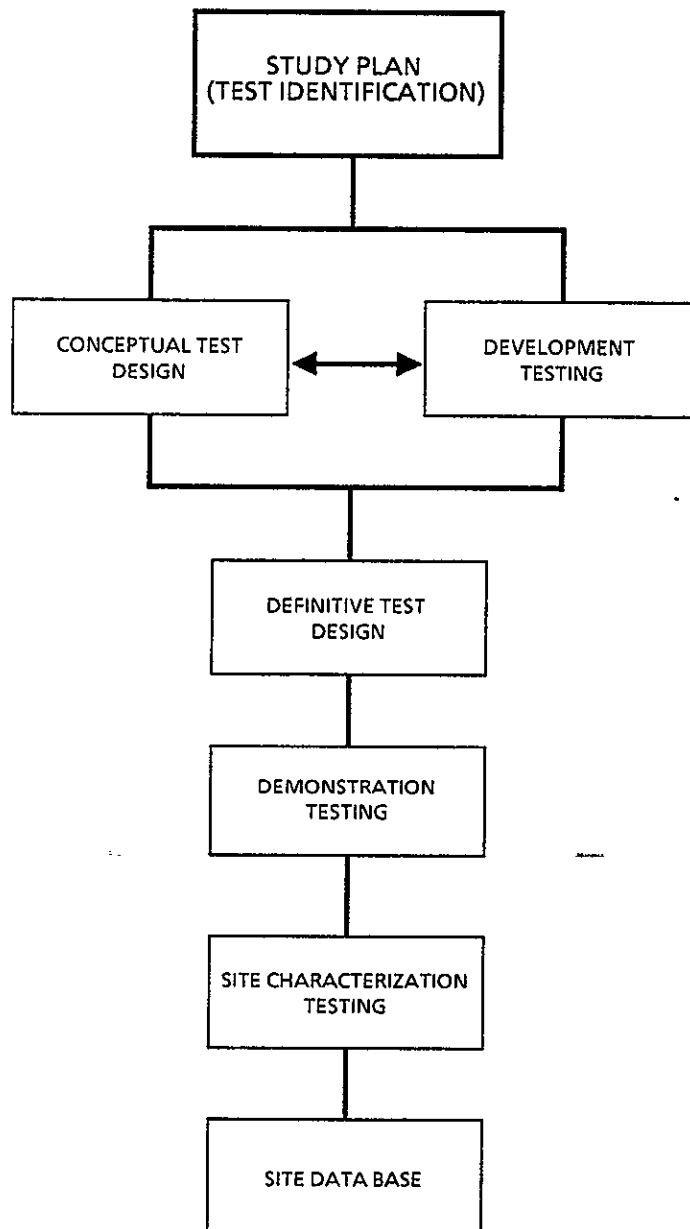
requirements imposed on the study. A simplified flow diagram of this process is shown in Figure 8.3.2.2-1. The process is essentially a two-phased design approach to test development. Following completion of the design, demonstration testing is performed to qualify the test for use in site characterization.

8.3.2.2.2 Rationale

Section 8.2 of the SCP uses the issue resolution strategy to establish what data are needed to design and license a repository in basalt. The goal of the issue resolution strategy, for the related key issues, is to develop a list of measurable parameters derived from regulatory requirements to assess the performance characteristics of the repository. The purpose of this section (8.3.2.2) is to describe the technical background and the constraints imposed by the regulatory requirements for the investigation of geomechanical characteristics of the host rock. The investigation has been formed to support the development of constitutive models (refer to Section 8.3.2.5.2) that describe the behavior of the repository host rock under changing conditions. Changes of the repository horizon environment from its natural state occur due to excavation of underground openings and emplacement of high-level radioactive waste. The need for an investigatory program to describe the rock mass constitutive relationship is based on design and performance assessment data and information needs. Specifically, it will be necessary to obtain engineering parameters that describe the mechanical, thermal, and thermomechanical behavior of the repository host rock as input parameters for the numerical models.

Tables 8.3.2.2-1 and 8.3.2.2-2 list the geomechanic parameters necessary for the resolution of certain performance and design issues. Performance parameters are shown in Table 8.3.2.2-1 with the issues from which they were derived. Table 8.3.2.2-2 is organized in a hierarchy of issue, system element, performance measure, performance goal, analytical tool, geomechanic parameter, and parameter goals. This method of presentation shows how the parameter is used (via the analytical tool) to determine measures of performance required to resolve the issue. When performance and parameter goals have not been established as indicated by a "TBD," determination of these goals is part of the issues resolution process. Performance parameters are subdivided into supporting parameters shown in Table 8.3.2.2-3. Table 8.3.2.2-3 includes the geomechanical analyses that require supporting parameters as input and includes the study from which these parameters will be derived. The exact, detailed parameters will be described in the study plans.

In addition, information is needed to validate the models and will be derived from tests that simulate repository conditions. Included in the investigation are studies to determine the in situ stress state and thermal and mechanical properties of the host rock, and to evaluate opening performance. These studies are described in detail in the four separate study plans referenced previously in this section.



PS87-2005-8.3.2-2

Figure 8.3.2.2-1. Test identification process.

Table 8.3.2.2-2. Geomechanics parameters (sheet 1 of 5)

Issue	System element	Performance measure	Tentative performance goal	Analytical tool	Geomechanics parameter	Tentative parameter goal
1.1	Engineered barriers subsystem	Radionuclide release rate from engineered barriers system (Ci/yr)	Ci/yr for ^{14}C (total repository)	Numerical modeling of groundwater flow, heat, and radionuclide transport (PMC-STAT, MAGNUM-2D, CHAINT-MC, REPREL, PORFLO)	Thermal conductivity, heat capacity	$> 10^7 \text{ J/m}\cdot\text{yr}\cdot\text{K}$ $> 700 \text{ J/kg}\cdot\text{K}$
	Repository seals subsystem	Cumulative release to the accessible environment through seals (Ci/Ci _{allowable})	Ci/Ci _{allowable} = 0.01	Numerical modeling of groundwater flow, heat, and radionuclide transport (PORFLO, PORFLO-3D, MAGNUM-2D, MAGNUM-3D, FECTRA, REPREL)	Thermal conductivity, heat capacity	$> 10^7 \text{ J/m}\cdot\text{yr}\cdot\text{K}$ $> 700 \text{ J/kg}\cdot\text{K}$
	Site subsystem	Cumulative release to the accessible environment through seals (Ci/Ci _{allowable})	Ci/Ci _{allowable} = 0.99	Numerical modeling of groundwater flow, heat, and radionuclide transport (MAGNUM-3D, FECTRA, PORMC)	Thermal conductivity, heat capacity	$> 10^7 \text{ J/m}\cdot\text{yr}\cdot\text{K}$ $> 700 \text{ J/kg}\cdot\text{K}$
1.4 and 1.5	Environment condition	Temperature profile through waste package		SINDA, TSAP, HEATING6	Temperature distribution	NA
		Mechanical load on waste package				NA
1.8	Rock alteration	Shear strength of joints for different degrees of rock alteration along joints	$< 30\%$ reduction of joint shear strength due to amount of alteration expected in 10,000 yr	TBD	Total stress profile, rock mass deformation, temperature distribution	TBD
	Rock or ground-water conditions requiring complex engineering measures	Change in hydraulic conductivity; creation of preferential pathways for fluid flow	TBD	TBD	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	TBD
		Container failure	TBD	TBD	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	TBD
		Large-scale failure of underground opening	TBD	Evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD

PST87-2005-8.3.2-14

Table 8.3.2.2-2. Geomechanics parameters (sheet 2 of 5)

Issue	System element	Performance measure	Tentative performance goal	Analytical tool	Geomechanics parameter	Tentative parameter goal
1.8 (cont.)	Geomechanical properties that do not permit design of stable underground openings	Ground deformation or inherent weakness of host rock	TBD	Constitutive model of rock mass	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	TBD
		Maintenance of accessible openings until permanent closure	TBD	Opening stability models, evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD
		Projected rock load on container greater than anticipated	TBD	Rock mass constitutive model for long-term behavior, evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD
		Rock bursts due to total stress/strain relationship cause loss of isolation	TBD	Evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD
1.11	NA	Vertical extent of postclosure caved area	Caving ≤ 3 times opening height	Numerical analysis of long-term effects of excavation, thermal loading, room geometry, and structural backfill on opening performance (ADINA, ADINAT, ABAQUS, ANSYS)	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	Caving ≤ 3 times opening height
1.12	Postclosure ground support to rock surrounding the borehole	Hydraulic conductivity of the damaged rock zone; transmissivity of the sealing backfill/damaged rock zone interface and sealing concrete/damaged rock zone interface	TBD	Analysis of thermal loading due to nuclear waste emplacement; analysis of mechanical interaction of sealing backfill with surrounding rock; evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD

PST87-2005-8.3.2-14

Table 8.3.2.2-2. Geomechanics parameters (sheet 3 of 5)

Issue	System element	Performance measure	Tentative performance goal	Analytical tool	Geomechanics parameter	Tentative parameter goal
1.12 (cont.)	Restrict ground-water flow	Hydraulic conductivity and transmissivity of sealing material/damaged rock zone interface	TBD	Groundwater flow and dispersion analysis	Temperature distribution, support system performance, damaged rock zone extent	TBD
2.4	Maintain access to and from emplaced waste	Access drift performance	TBD	Ground support selection (Q-method, RMR method, site-specific method), opening stability analysis, dynamic effects on stability	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	(See Table 8.2.2.2.4-2)
		Shaft performance	TBD	Ground support selection (Q-method, RMR method, site-specific method), opening stability analysis, dynamic effects on stability	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	(See Table 8.2.2.2.4-2)
	Retrieval of waste container from emplacement borehole	Container performance	TBD	Numerical models of container/waste package integrity	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	(See Table 8.2.2.2.4-2)
		Borehole performance	TBD	Opening stability analysis	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD
2.7	Retrieval	Maintain exposure limits	TBD	Numerical model of borehole integrity	Total stress profile, rock mass deformation, temperature distribution, damaged rock zone extent	TBD
			TBD	Numerical model of waste package integrity	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD

PST87-2005-8.3.2-14

Table 8.3.2.2-2. Geomechanics parameters (sheet 4 of 5)

Issue	System element	Performance measure	Tentative performance goal	Analytical tool	Geomechanics parameter	Tentative parameter goal
2.7 (cont.)	Access construction	Stability of underground openings	Stable openings through retrieval period	Mechanical and thermal analyses	All	See Issue 2.4 (Table 8.2.2.2.4-2)
	Drift construction	Stability of underground openings	Stable openings through retrieval period	Mechanical and thermal analyses	All	See Issue 2.4 (Table 8.2.2.2.4-2)
	Borehole construction	Stability of underground openings	Stable openings through retrieval period	Mechanical and thermal analyses	All	See Issue 2.4 (Table 8.2.2.2.4-2)
	Groundwater control	Stability of underground openings	Stable openings through retrieval period	Mechanical and thermal analyses	All	See Issue 2.4 (Table 8.2.2.2.4-2)
	Operational maintenance	Stability of underground openings	Stable openings through retrieval period	Mechanical and thermal analyses	All	See Issue 2.4 (Table 8.2.2.2.4-2)
		Stability of underground openings	TBD	Opening stability analysis, dynamic/seismic analysis (FLUCH, ANSYS, STARDYNE), ground support selection (Q-method, RMR method, site-specific method) Evaluation of opening performance, observation and experimental analysis, performance of selected profiles and methods	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	TBD
4.2	NA	Adequate quantity and quality of air sufficiently refrigerated to comply with MSHA (1987) and ACGIH (1987) standards to maintain satisfactory working environment	See Issues 2.4 and 2.7	Airflow distribution: VNET; constructibility analysis: HVAC; air cooling analysis: CLIMSIM	Temperature distribution, damaged rock zone extent	See Issues 2.4 and 2.7
		Lining from surface to top of basalt retains sufficient integrity to prevent inflows of water and (or) noncohesive overburden material	See Issues 2.4 and 2.7	Structural design analysis/constructibility analysis/dynamic effects on stability	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	See Issues 2.4 and 2.7

PST87-2005-8.3.2-14

Table 8.3.2.2-2. Geomechanics parameters (sheet 5 of 5)

Issue	System element	Performance measure	Tentative performance goal	Analytical tool	Geomechanics parameter	Tentative parameter goal
4.2 (cont.)	NA	Prevention of collapse and control of rock falls Limiting unacceptable overstress concentrations Limitation of induced stress to acceptable level	See Issues 2.4 and 2.7	Opening stability analysis, thermal/thermomechanical analysis, ground support selection (Q-method, RMR method, site-specific classification); evaluation of opening performance	Total stress profile, rock mass deformation, temperature distribution, support system performance, damaged rock zone extent	See Issues 2.4 and 2.7

ACGIH = American Conference of Government Industrial Hygienists.

MSHA = Mine Safety and Health Administration.

NA = Not applicable.

PAC = Potentially adverse condition.

RMR = Rock mass rating.

TBD = To be determined.

PST87-2005-8.3.2-14

Table 8.3.2.2-3. Geomechanics supporting parameters (sheet 1 of 3)

Performance parameter	Geomechanics analyses required	Supporting parameter	Test basis			Study
			Current estimate	Current confidence	Needed confidence	
Rock mass deformation	Thermomechanical stress analyses validated by in situ tests	Natural in situ stress tensor	$\sigma_1 = 62 \text{ MPa}$ (N. 06 E.)	Low	Medium	8.3.2.2.3.1
			$\sigma_2 = 33 \text{ MPa}$ (N. 84 W.)	Low	Medium	8.3.2.2.3.1
			$\sigma_3 = 24 \text{ MPa}$ (vertical)	Low	Medium	8.3.2.2.3.1
		Excavation induced stress	TBD	Low	Medium	8.3.2.2.3.1
		Thermally induced stress	TBD	Low	Medium	8.3.2.2.3.1
		Deformability				
		- Intact rock	$E = 73 \text{ GPa}$ $\nu = 0.25$	Low	Medium	8.3.2.2.3.3
		- Rock mass	$E = 73 \text{ GPa}$ $\nu = 0.25$	Low	Medium	8.3.2.2.3.3
		- Creep	$E = 73 \text{ GPa}$ $\nu = 0.25$	Low	Medium	8.3.2.2.3.3
		Strength				
		- Intact rock	305 MPa (uniaxial)	Low	Medium	8.3.2.2.3.3
		- Rock mass	TBD	Low	Medium	8.3.2.2.3.3

PST88-2014-8.3.2-2

Table 8.3.2.2-3. Geomechanics supporting parameters (sheet 2 of 3)

Performance parameter	Geomechanics analyses required	Supporting parameter	Test basis			Study
			Current estimate	Current confidence	Needed confidence	
Rock mass deformation (cont'd)	Thermomechanical stress analyses validated by in situ tests	Joint properties:				
		- Normal stiffness	$K_n = A(1 + Br_n)^2$ $A = 40.2 \text{ MPa}$ $B = .2764$	Low	Medium	8.3.2.2.3.3
		- Shear stiffness	550 GPa/m	Low	Medium	8.3.2.2.3.3
		- Strength	$\phi = 37.4$ $c = 1.6 \text{ MPa}$	Low	Medium	8.3.2.2.3.3
		Thermal properties				
		- Conductivity	1.51 W/m °C	Low	Medium	8.3.2.2.3.2
		- Heat capacity	0.929 kJ/kg °C	Low	Medium	8.3.2.2.3.2
		- Expansion coefficient	$6 \times 10^{-6}/^\circ\text{C}$	Low	Medium	8.3.2.2.3.2
		- Initial temperature	55 °C	Medium	Medium	*
		- Thermal gradient	4 °C/100 m	Medium	Medium	*
	Direct observation	Opening deformation	--	--	--	8.3.2.2.3.4
		Rock failure characteristics	--	--	--	8.3.2.2.3.4
Total stress profile	Field measurements	Natural in situ stress tensor	$\sigma_1 = 62 \text{ MPa}$ (N. 06 E.) $\sigma_2 = 33 \text{ MPa}$ (N. 84 W.) $\sigma_3 = 24 \text{ MPa}$ (vertical)	Low	Medium	8.3.2.2.3.1

PST88-2014-8.3.2-2

Table 8.3.2.2-3. Geomechanics supporting parameters (sheet 3 of 3)

Performance parameter	Geomechanics analyses required	Supporting parameter	Test basis			Study
			Current estimate	Current confidence	Needed confidence	
Total stress profile (cont'd)		Excavation-induced stress	TBD	Low	Medium	8.3.2.2.3.1
		Thermally induced stress	TBD	Low	Medium	8.3.2.2.3.1
Temperature profile	Thermal analyses	Thermal properties				
		- Conductivity	1.51 W/m °C	Low	Medium	8.3.2.2.3.2
		- Heat capacity	0.929 kJ/kg °C	Low	Medium	8.3.2.2.3.2
		- Rock mass temperature	NA	High	Medium	*
Damaged rock zone extent	Thermomechanical stress analyses validated by in situ tests Direct observation	Parameters listed above under rock mass deformation				
		Rdial extent of damaged rock zone	2 m	Low	Medium	8.3.2.2.3.4
		Construction parameters	TBD	Low	Medium	8.3.2.2.3.4
Support system performance		Ground support type and characteristics	TBD	Low	Medium	8.3.2.2.3.4
		Load on support components	TBD	Low	Medium	8.3.2.2.3.4
		Shotcrete/grout bonding quality to rock	TBD	Low	Medium	8.3.2.2.3.4

*Current understanding of the ambient host rock temperature is considered adequate (Section 1.3.2.5.1.1).

TBD = To be determined.

To convert MPa to lbf/in², multiply by 1.450 x 10².

To convert GPa to lbf/in², multiply by 1.450 x 10⁵.

PST88-2014-8.3.2-2

8.3.2.2.2.1 Technical background

Technical background for the investigation of geomechanical characteristics of the host rock revolves around the following three conditions:

1. Preexcavation.
2. Postsubsurface excavation/pre-waste-emplacment.
3. Post-waste-emplacment.

Evaluation of the preexcavation host rock environment provides baseline information. Stress redistribution and deformation of the rock mass around the openings resulting from subsurface excavation (the postsubsurface excavation/pre-waste-emplacment condition) could have an effect on other parameters, all of which must be examined. Emplacement of heat-generating waste will lead to changes in the host rock environment and could alter the mechanical and physical properties of the rock, which in turn may influence the performance of seals and rock/waste package interaction. The separation of the host rock environment into three distinct categories is somewhat artificial in that the transition of the rock mass from one to another is a continuum relationship dependent on the undisturbed conditions of the rock mass, rock mass properties, repository construction and operation activities, and time. Thus, constitutive relationships should be developed to encompass as many aspects of the host rock environment as practical.

8.3.2.2.2.1.1 Preexcavation.

The basis of the evaluation of the preexcavation host rock environment is the need for a quantitative description of the natural conditions and properties of the rock mass in which the repository will be constructed. The evaluation will be accomplished by an extensive program of testing and analysis, conducted both in the laboratory and in the Exploratory Shaft Facility. (The subsurface layout is described in Section 8.4.2.2.1.1.) The properties and conditions determined through this investigation will serve as the baseline for fundamental calculations of rock behavior and as input parameters in numerical models that predict the rock behavior on a more comprehensive scale. This portion of the investigation is divided logically into three studies to determine the in situ stress state, thermal properties, and mechanical properties of the host rock.

Parameters describing the natural host rock environment can be broadly divided into two groupings. The first grouping of parameters describes the existing conditions within the rock mass, such as geologic structure, hydrologic regime, ambient temperature distribution, and in situ stress state. Plans for characterization of the geologic structure of the host rock and the hydrologic regime are discussed in Sections 8.3.1.2 and 8.3.1.3, respectively; and the current understanding of the ambient temperature in the host rock, as discussed in Section 1.3.2.5.1.1, is considered to be adequate. This leaves the determination of the in situ stress state as the pertinent study to be performed under this grouping.

Information to be obtained regarding the preexcavation host rock environment in the in situ stress study will be the magnitude and direction of the natural in situ stress state acting within the host rock, both within the reference repository location and on a regional scale. Stress is a tensor quantity, defined by the magnitude and direction of three orthogonal principal stresses, or by the magnitudes of normal and shear stress components acting in a given coordinate system. The natural stress state represents the baseline value on which induced stresses resulting from excavation and waste emplacement are superposed. Natural stresses in the host rock result from gravitational loading, geologic structure, contrasts in rock mass deformational characteristics, and tectonic activity. The natural stress can vary with location, depth, material type, and local geologic structure. Information gained through this study will be evaluated with regard to these variables.

The second grouping of parameters describing the natural host rock environment indicates how the rock mass responds to stimuli (e.g., changes in stress state and temperature) that would be imposed on it by construction and operation of a repository. Because of the number of parameters included in this grouping, a division was made between mechanical and thermal properties to arrive at the studies to be performed.

The study of the thermal properties of the host rock will provide information on both the thermal and thermomechanical properties of the host rock in its natural environment. The thermal properties of the host rock can be considered as a composite of the properties of the matrix rock comprising the rock mass and the properties of discontinuities (primarily fractures and fracture-infilling materials). Thus, the thermal properties study must include measurements made in the laboratory on intact rock specimens, laboratory measurements on fracture-infilling materials and specimens with oriented fractures, and in situ measurements at rock mass scale. Determination of the properties for the rock mass will be based on a combination of the results of these measurements. The specific properties to be determined in this study are thermal conductivity, heat capacity, and the coefficient of thermal expansion.

Information to be provided by the mechanical properties study will include the mechanical and physical properties of both the parent host rock material and major discontinuities (joints). These properties will be determined through an integrated program of laboratory testing and tests in the Exploratory Shaft Facility to determine properties of the host rock at the rock mass scale. The mechanical properties provided by laboratory testing on intact rock will include deformability, tensile strength, and compressive strength over a range of confining stresses. At present, deformability is the primary parameter to be investigated at the rock mass scale, although every reasonable effort will be made to measure rock mass strength in situ. These measurements will be supplemented as necessary with values from empirical correlations. If it is not possible to conduct in situ strength tests, rock mass values will be estimated empirically. Mechanical properties of joints to be evaluated are the peak and residual shear strength, normal stiffness, shear stiffness, and friction angle. The dependence of mechanical properties on

temperature, location, and intraflow structure will be determined within the mechanical properties study. Creep properties of the host rock will also be studied.

A major consideration in the quantification of material properties for the host rock is that of scale. Since rock is not a homogeneous material, its properties will vary with the volume of rock under observation. The rock mass can be considered a composite material consisting of the matrix rock and inhomogeneities (e.g., vesicles, vugs) transected by geologic discontinuities such as fractures. The main effect of discontinuities within the rock mass will be a change in the strength, deformability, hydrologic properties, and thermal properties of the rock from those determined through laboratory tests on small intact specimens. As the volume of observation is increased, more and more discontinuities are included until a scale is reached wherein the rock mass can be represented by an equivalent homogeneous material. Assessment of the validity of a continuum approach and the quantitative description of an equivalent material is a major objective of investigating the host rock environment (see Section 8.3.2.5.2.3). The major concern in rock properties determination is whether the results of a given test accurately represent the rock mass or whether the results can be extrapolated to rock mass scale with confidence. To address this concern during site characterization, laboratory tests will be conducted to simulate, within practical limitations, a range of expected underground conditions with respect to temperature, stress, and, in some instances, pore pressure. Laboratory testing will be integrated with field testing in the Exploratory Shaft Facility, empirical and analytical methods, full-scale observations, and case histories to arrive at properties for the rock mass. These activities will be integrated with the development and validation of material models (Section 8.3.2.5) to ensure that adequate data will be obtained.

8.3.2.2.1.2 Postsubsurface excavation/pre-waste-emplacement.

Creation of manmade openings in the repository host rock will alter the host rock environment in a volume of rock immediately surrounding the openings and extending some distance away from the opening. Outside this volume of rock, the mechanical disturbance due to the excavation is negligible. The two primary effects of excavation on the host rock environment are stress redistribution and deformation of the rock mass around the opening. These induced effects can adversely impact the hydrologic regime through deformation-induced hydrologic pathways and the opening performance through mechanical response to the induced stresses.

The evaluation of the postsubsurface excavation/pre-waste-emplacement conditions includes studies and observations on the effects of construction of repository openings on the characteristics of the host rock mass (including rock mass engineering properties and excavation induced damage), the performance and constructability of prototypic openings, and the induced stresses and displacements around these openings. Effects of excavation will be addressed in a study to evaluate opening performance (refer to Section 8.3.2.2.3.4). Additionally, the three studies to determine the

natural conditions of the host rock (in situ stress determination, mechanical properties determination, and thermal properties determination) will be extended to include excavation effects.

Information to be obtained in the in situ stress study will be in the form of post-excavation stress profiles (both magnitudes and directions) around representative openings in the Exploratory Shaft Facility. The stress profiles will be based on in situ stress measurements made at progressive distances away from the opening. This information will be obtained in conjunction with the natural in situ stress in the host rock, because induced stresses are necessarily dependent on the magnitude and orientation of the background stresses on which they are superposed. Because most rock cannot be considered homogeneous, in situ stress magnitudes and orientations will vary with location, depth, and overall rock quality. Stresses may arise as a direct result of the excavation process, or as subsequent mechanical degradation of the rock mass in response to changes in the stress state. These variables affect both natural and induced stresses. Additional variables that affect induced stresses are geometry of openings, extent of rock damage from excavation, interaction with rock support systems, and time. There also may be variations in determined stresses due to the stress determination method used. The induced stress information resulting from this study will incorporate an evaluation of all these variables.

Changes in the mechanical, physical, and thermal properties of the rock can be induced by excavation damage and dilatancy of the rock mass. Subsequent failure of this mechanically weakened rock may promote further properties changes. Opening stability is dependent on structurally controlled phenomena such as block rotation, slippage, and fallout on preexisting fractures, as well as possible crumbling, spalling, and slabbing in locally overstressed zones. The intent of this study is to characterize the changes to the host rock environment resulting from excavation as they relate to opening performance and changes in the mechanical, physical, and thermal properties of the host rock. Information to be obtained in the opening performance study relating to the post-subsurface-excavation/pre-waste-emplacement environment will include data on the deformation response of prototypic repository openings during and after construction, performance data on prototypic rock support systems, data on the mechanical characteristics of damaged rock surrounding the excavation, and data on the deformational and strength characteristics of the rock mass. Analyses of these data will be based on assessments of variables and deformational mechanisms that may influence and control opening response. Some of these variables are geologic conditions, joint characteristics, column structure, geometry of the openings, time, stress, and support system interaction.

In the design of a repository, the behavior of the rock mass in response to excavation will be examined by empirical and analytic methods as part of model validation. Results of the modeling effort will be used to design the underground layout, optimize the size and shape of the openings, determine roof support requirements, and predict stress concentrations and displacement. For the particular purposes of designing a radioactive waste repository, the numerical model must support prediction of long-term behavior and must be developed to exhibit adequate confidence for these predictions. Such models

inherently employ several assumptions as a result of the complexity of the system being modeled and the uncertainty of the parameters used in the analysis. The adequacy of the model is validated by comparing the model's prediction to the results of a full-scale simulation of the system. The opening performance study will provide data for validation of the models from conditions representative of those expected in the repository.

If significant discrepancies exist between the model results and the results of the field test, the cause of the discrepancies must be determined and corrected before the model can be used with confidence. Disagreement between measurements and predictions can often be attributed to the parameters used in the model, the assumptions inherent in the model, or the selection of the phenomena to be addressed in the model. Errors in the conceptual models used for analysis (i.e., geometry, boundary conditions, initial conditions) may also introduce a significant source of error if data from the geology and geophysics programs (Section 8.3.1.2) are not carefully treated. The problems of uncertainty in conceptual models are discussed further in Section 8.3.2.5. Inability to correctly model the rock mass behavior may also occur because of uncertainty in rock conditions (e.g., moisture content, anisotropy, and inhomogeneity of the rock mass). Instrument, measurement, and algorithm errors may occur. Refinement of the model will increase confidence in its predictive capabilities; however, because of the relatively short-term in situ testing, long-term validation may be possible only qualitatively.

8.3.2.2.2.1.3 Post-waste-emplacement.

The investigation of host rock characteristics will include characterization of the response of the repository host rock to temperatures representative of those expected in the repository. Response of the rock will be characterized by evaluating thermally induced stresses and opening performance. Introduction of heat into the host rock from emplacement of heat-generating waste will lead to changes in the host rock environment. Elevated temperature will mobilize thermal expansion of the rock mass, which will result in increased stresses. The effect of thermally induced stress will be increased deformation and loading around repository openings.

The thermally induced stress state will be determined in conjunction with the natural and excavation-induced stress states. The total stress state in the host rock at a given location will be a function of the natural stresses, excavation induced stresses, and thermally induced stresses. Information to be gathered relating to the post-waste-emplacement host rock environment will be in the form of stress changes as a function of temperature and total stress profiles around a room opening at selected temperatures. These data will be evaluated with regard to the amount of damage to the rock surrounding underground openings, thermal expansion of the rock mass as it relates to opening stability, and to the possible creation of thermally induced hydrologic pathways.

The study of opening performance will be extended to include the post-waste-emplacement host rock environment by conducting a room-scale heater

test. The information collected in this study will include deformation response of the rock at expected repository temperatures, stability of a representative emplacement borehole and drift, and evaluation of thermally induced fracturing in the host rock. This information will be evaluated with regard to scale, geologic conditions, time, and fracture characteristics.

Model validation studies discussed in Section 8.3.2.5 must include the post-waste-emplacement environment since modeling simulations will necessarily incorporate the thermal effects from waste emplacement. This requires that large-scale, prototypic simulation tests be performed in the Exploratory Shaft Facility. Because of time and scale constraints, it is not possible to recreate the exact thermal conditions expected in a repository. However, large-scale thermal tests that are amenable to numerical modeling can be performed for this validation effort. Such tests can approach expected repository conditions within an acceptable degree by proper design of the test boundary conditions and operating parameters.

Characterization of the post-waste-emplacement host rock environment is required. Site characterization activities and modeling studies will evaluate the effects, stresses, and displacements induced by construction and heating may have on the repository seals and the waste package design. One of the major concerns is the influence these effects will have on the extent of the disturbed zone annulus around openings, and associated changes in the hydrologic and geochemical properties. Assessment of these influences will require a coordinated effort between geomechanics, hydrology, geology, and geochemistry personnel.

Stability of the opening is to be provided for repository worker protection and for maintenance of retrievability prior to permanent closure of the repository. Stress and deformations resulting from thermal loadings must be considered in the design of the repository for these purposes.

Retrievability could be impacted by block or creep movements of the rock mass immediately surrounding an emplacement borehole. Block movements could result from increased stress around the emplacement borehole acting on fractures of low angular orientation relative to the stress direction. Basalt creep is not expected to be significant, but long-term movements at joints should be examined. Joint filling and characteristics could enhance or diminish the likelihood of such block and creep movements.

Containment could be impacted if resultant deformation creates increased hydraulic communication with adjacent aquifers. The potential for increased hydraulic communication could come from thermally induced fractures or changes in the openings of existing fractures or joints. Further, the design and installation of permanent repository seals must be done with consideration of long-term thermal behavior.

8.3.2.2.2 Constraints

Several constraints exist in the evaluation of the geomechanical properties of the host rock environment. Some of the more pertinent general

constraints are discussed in the following paragraphs. More detailed descriptions of the constraints specific to each study are presented in the study plans for each study comprising the investigation.

8.3.2.2.2.1 Sample availability.

Prior to construction of the Exploratory Shaft Facility, virtually all laboratory test specimens will be obtained from the inventory of core materials archived in the BWIP Core Library. The two factors that tend to constrain the availability of samples from the inventory for testing purposes are (1) many dense interior zones in the cores exhibit a high degree of disk fracture development that reduces the proportion of fracture-free intervals in core that are suitable for intact strength testing, and (2) extensive sampling from the remaining fracture-free intervals already has been performed in the past.

8.3.2.2.2.2 Sample orientation.

Characterization of anisotropic behavior and of the vertically oriented fracture frequency is impeded because of the vertical orientation of all existing core from the reference repository location.

8.3.2.2.2.3 Sample condition.

A small amount of damage to test specimens is unavoidable. This damage results from drilling and sampling procedures, handling and storage, and preparation of specimens for testing. Such damage is not expected to be significant, but it is a constraint to be considered in the evaluation of laboratory test results. A second general constraint is that the BWIP core inventory exists in an "air dry" condition. As a result, there is no current source of samples for testing of fracture characteristics under in situ moisture conditions.

8.3.2.2.2.4 Access.

Determination of the host rock properties at rock mass scale will not be possible until after the Exploratory Shaft Facility is constructed and available for testing. Prior to this, the only access to the host rock will be through surface drilled boreholes. Additionally, in terms of stress determination, access to the undisturbed host rock in the repository horizon after construction of the facility is only possible through long, horizontal boreholes drilled from the periphery of the facility.

8.3.2.2.2.5 Available technology.

Tests, both in situ and in the laboratory, are constrained by the current state of the art in rock mechanics. This includes instrumentation limits, accuracy and precision, methods of data analysis, and the current state of development of in situ testing methods (Perko, 1986; St. John et al., 1982).

8.3.2.2.2.2.6 In situ testing limitations.

Several constraints apply for tests that are to be conducted within the Exploratory Shaft Facility:

1. Most in situ tests are large, complex, and costly, requiring long time periods to construct and conduct.
2. In most cases, only a limited number of test repetitions are feasible to perform; therefore, no statistical treatment of the test results is possible and the uncertainty cannot be directly quantified.
3. There is a limited amount of control over test variables in a typical in situ test. In addition, it is difficult to fully characterize the volume of rock tested in a large-scale experiment, e.g., the number, location, and conditions of fractures.
4. There is limited control over test locations because of the size of the facility and potential for interference with other site characterization activities.
5. Environmental conditions are more severe in the Exploratory Shaft Facility than at the surface and may require special instrumentation.
6. Testing must be performed within a limited schedule.

8.3.2.2.2.2.7 Schedule constraints.

The schedule for Exploratory Shaft Facility testing is limited by access to underground test facilities (time to start of construction and construction time) and the required date for submittal of a license application and accompanying design. This will limit the time available to implement in situ tests, collect and analyze data, validate constitutive models, apply validated models in the design of the facility, conduct performance assessments of the facility, and report results.

8.3.2.2.2.2.8 Interference with other site characterization activities.

Two potential sources of interference with other site characterization activities have been identified--interference with hydrology testing and interference with ongoing mining and operations. No interference, in terms of the zone of test influence, will be allowed between rock mechanics and hydrologic tests. Typically, hydrologic tests will encompass a large volume of rock and will be susceptible to small changes in the host rock environment, such as the presence of other test boreholes in the hydrologic test volume. Some interference with construction activities and ongoing operations of the Exploratory Shaft Facility can be expected during the normal course of the

site characterization; however, construction activities are short in duration compared to the testing time. The impact of this interference will be minimized by careful logistical planning.

8.3.2.2.3 Description of studies

The investigation of geomechanical characteristics of the host rock consists of four studies dealing with in situ stress, mechanical properties, thermal properties, and opening performance. Each study is comprised of tests and analyses that are described briefly in Sections 8.3.2.2.3.1 through 8.3.2.2.3.4.

Test development described by the study plans will include evaluation of specific laboratory and in situ testing requirements as well as current testing capabilities. Available technology will be used to the extent possible. However, it is recognized that in many circumstances, present testing capabilities may be inadequate for anticipated conditions in the Exploratory Shaft Facility. Where necessary, the development program for a specific test or group of tests will evaluate the feasibility of achieving sufficient test capabilities to obtain meaningful results. If the outcome of the feasibility study indicates that such capability is not likely to be attained, alternative test methods will be considered.

8.3.2.2.3.1 In situ stress determination study

The in situ stress determination study consists of tests and analyses to obtain quantitative estimates of both natural and induced in situ stress magnitudes and orientations. The objective of the study is to provide in situ stress data required for site characterization, repository design, and performance assessment. The study of in situ stress determination will provide a more complete description of the tests and analyses.

The primary tests and supporting tests and analyses being considered for inclusion in the in situ stress determination study are shown in Table 8.3.2.2-4. The table also includes reference to the pertinent performance issues and design issues requiring the parameters to be determined through the study. Supporting tests and analyses shown in the table will not be used to determine stress directly, but are proposed elements of the study that enhance the determination of stress through the primary test methods shown. Each method for in situ stress determination has its own unique characteristics, advantages, and limitations for use under a given set of conditions. Planning for the in situ stress study program involves selecting the most appropriate test method for each situation and evaluating the results. When tests are unsuccessful or unanticipated conditions are encountered, a different test method can be used. Contingencies will be addressed in an ongoing effort to evaluate the success of the in situ stress testing program, including performing developmental tests at the Near-Surface Test Facility. Test methods for in situ stress determination at the BWIP were selected on the basis of compatibility with anticipated data requirements,

Table 8.3.2.2-4. In situ stress tests, studies, and supporting analyses

Investigation	Study	Performance issues	Design issues	Parameter	Primary tests	Supporting tests and analyses
Geomechanical characteristics of the host rock	In situ stress	1.4 1.5 1.8 2.4	1.11 1.12 2.7 4.2	Natural stress state	Overcoring Hydraulic fracturing	Differential strain analyses Disking study Borehole spalling study Residual stress study Correlation with tectonics and structural geology Geophysics tests: • Sonic log • Borehole televiewer log
				Excavation-induced stress state	Overcoring Small flat jacks	Dilatometer Rock support interaction Deformational properties Mine-by tests Damaged rock characterization Rock support interaction Repository seals tests Geophysics tests: • Sonic log • Borehole televiewer log
				Thermally induced stress state	Overcoring Small flat jacks	Full-scale heater test: • Borehole pressure cells • Stressmeters Thermal expansion test Deformational properties Damaged rock characterization Time-dependent behavior (creep) Geophysics tests: • Sonic log • Borehole televiewer log

PST87-2005-8.3.2-13

geologic conditions, rock quality, operational requirements, and expected test conditions. Additional data will be obtained from supporting tests and analyses.

Discussion of the in situ stress study in this section will concentrate on the independent variables that will affect the determination of in situ stresses. In situ stress magnitudes and orientations vary with location, depth, material type, and overall rock quality. There may also be variations related to the stress determination method used. These variables affect both natural and induced stresses. Additional variables that affect induced stresses are geometry of openings, extent of damaged rock around openings, rock support interaction, time, and the effects of elevated temperature. The study is organized to evaluate the effects of these variables.

The in situ stress state will vary laterally within the repository host rock because of geologic structure, variations in rock type and (or) rock quality, and major discontinuities within the rock mass such as faults or joints. Rock quality refers to the nature and degree of fracturing and jointing present in the rock mass. The presence of such discontinuities within the rock mass can have a significant effect on the local stress distribution. Rock quality factors that may affect in situ stress determination include fracture or joint spacing, orientation, aperture, roughness, filling, and the presence of fluid within the joints. Lateral variability of stress will be evaluated by conducting tests from surface boreholes around the Hanford Site and the reference repository location and by tests in several locations performed in boreholes at the Exploratory Shaft Facility. Stresses will be determined at each location with respect to a complete geologic and rock quality description of the rock mass.

Horizontal variability of in situ stress over the controlled area study zone will be addressed by an integrated evaluation of hydraulic fracturing test data that also takes into account other qualitative indications of in situ stress (i.e., core diskings, borehole spalling, and geologic structure).

Hydraulic fracturing tests are the only practical means of stress determination in deep boreholes under conditions present at the Hanford Site. They are time consuming and expensive and may interfere with other important tests. In addition, it is desirable to limit the number of boreholes penetrating the repository horizon. An integrated approach that considers all stress-related phenomena should help to improve the level of confidence in the numerical values obtained from hydraulic fracturing. The total number of holes in which hydraulic fracturing tests are conducted will ultimately depend on the outcome of the data evaluation process and the level of confidence required.

Differential strain analysis is a laboratory test that may provide semi-quantitative stress data from core samples. A preliminary investigation and evaluation program is planned to determine the feasibility of differential strain analysis as a stress measurement technique at the Hanford Site. If this technique should prove reliable as a stress determination method, then it

will be possible to obtain significantly more in situ stress data at relatively little additional cost and minimal interference with other testing. This will be of great benefit in evaluating horizontal variability of in situ stress.

To estimate spatial variability of in situ stress within the Cohasset flow, results from hydraulic fracturing tests and core disk and borehole spalling data will be examined. Existing hydrofracturing data have been collected from three holes within the reference repository location. Additional tests are planned in approximately four to six holes located within the controlled area study zone. The exact number is dependent on availability due to hydrologic testing.

Sensitivity studies are anticipated to show a strong relationship between in situ stress and repository design. Factors such as opening configuration, opening dimensions, layout of the openings, and waste emplacement density are expected to be sensitive to both magnitude and orientation of in situ stress. In view of the large area required for repository construction (approximately 8.3 km^2 (3.2 mi^2)), spatial variability of the in situ stress field must be evaluated to determine the range of stress values for which the repository must be designed. On a regional scale, evaluation of spatial variability in the in situ stress field is an important component in correlation of stress determination data with geologic structure, stratigraphy, and the regional tectonic setting.

In situ stress magnitudes will be determined as a function of depth. Vertical stress increases with depth as a consequence of the increasing weight of overburden. Horizontal stresses will tend to increase with depth since, under conditions of lateral confinement, they are related to vertical stress by Poisson's effect. Other factors, such as tectonic stresses, thermal history, geologic structure, and variations in modulus also result in variations in in situ stress with depth.

Evaluation of stress at each test location will be based on local mechanical properties of the rock mass because variations in elastic properties may be expressed as variations in stress magnitude. For example, if a uniform load is applied parallel to the layers of a medium in which each layer has a different value of elastic modulus, the composite system must distribute the load so that all deformations are equal. Hence, the stiffer layers will carry a greater portion of the load and will experience greater stress. Variations in rock quality have the same effect to the extent that they affect rock mass properties, such as modulus of deformation.

The effects of the measurement method on in situ stress determination will be an essential element of this study. In most cases, it is impossible to directly measure stress. The in situ stress state is typically determined by inducing a change in the local stress field and measuring the subsequent behavior of the rock mass as it responds to this change. The in situ stress state is then determined, using appropriate relationships and material properties for the measurement method in use. Therefore, the stresses determined from a particular type of test are dependent on the assumed or

determined material properties and boundary conditions associated with the test. Compatibility of the test being used with the host rock must be considered; this will be accomplished by proof-of-principle and developmental testing in the laboratory and Near-Surface Test Facility.

Magnitude and orientation of induced stress are dependent on the geometry of underground openings. The size and configuration of an underground opening and its orientation with respect to the principal in situ stresses are important factors that control induced stresses in the vicinity of the excavation. Measurements will be made around openings of different configurations to determine stress profiles as a function of opening geometry.

Influence of damaged rock on excavation and thermally induced stresses will be investigated in this study. The extent of damaged rock around mined openings affects the stress distribution, because it represents a zone in which the rock strength and deformational properties are altered as a result of the mining operation.

Rock support elements such as shotcrete, rock bolts, or steel sets are capable of supporting a small portion of the stress in the rock mass surrounding an excavation. More importantly, the support system provides kinematic restraint and confining stress that greatly enhance the strength of the rock mass so that the rock, not the support, carries the load. Because stresses are redistributed by interaction of the rock mass with the rock support elements, rock support impacts the distribution of induced stresses within the rock mass; hence, measurement of load on rock support elements and induced stress will provide information on the interaction of stress with the rock support system.

The study also includes time-dependent stress measurements. Although classical elastic theory would predict that all deformations and stress redistributions will occur within a very short time period after excavation, rock materials tend to exhibit some degree of time-dependent behavior. Therefore, the induced stress about an opening, and (or) thermally induced stresses, may show some variation as a function of time as loads are redistributed within the rock mass.

Primary test descriptions are provided in Sections 8.3.2.2.3.1.1 through 8.3.2.2.3.1.3.

8.3.2.2.3.1.1 Overcoring.

In situ stress determination by overcoring is based on the concept that the rock behaves elastically and that deformations or strains associated with stress relief are equivalent (although opposite in sign) to the deformation/strain that would occur if the same stress field were to be imposed on the unstressed rock. An overcoring cell is installed in the rock mass and initial strain or deformation readings are made. Stresses are then relieved by coring the volume of rock containing the cell. As the core bit passes the cell location, the rock deforms in response to stress relief. By measuring the deformation or strain and the elastic properties of the rock, it is possible

to compute the in situ stress state of the rock mass from elastic theory. When only diametral deformations or strains are measured, the two secondary principal stresses in the plane perpendicular to the borehole axis can be determined. If deformation/strain along the borehole axis can also be measured, the complete stress tensor can be determined from a single test.

Three of the overcoring cells to be used in the Exploratory Shaft Facility are (1) the U.S. Bureau of Mines borehole deformation gage, (2) the Australian CSIRO (Commonwealth Scientific and Industrial Research Organization) triaxial cell, and (3) the South African CSIR (Council for Scientific and Industrial Research) "doorstopper" cell. Because each instrument is based on the same general principle, it is treated as a single test except where individual differences warrant separate discussion.

Selection of overcoring cells for the Exploratory Shaft Facility is based on the need to adapt to a number of known and anticipated rock conditions and equipment constraints. Although testing in the Near-Surface Test Facility has shown that overcore results exhibit considerable scatter in basalt, these same data also demonstrate that overcoring can be performed successfully in highly jointed rock. (However, it is likely that much of the scatter in the results can be attributed to the relatively low stress levels present in the Near-Surface Test Facility.) It is a possibility that the scatter in the data and the test failure rate will be higher in jointed basalt than in a more massive rock, but this can be partially overcome by conducting more tests. Core diskings poses problems for overcoring, and assessing its impact will be a component of future development work.

The overcoring instruments mentioned above have been selected because each has specific characteristics that mitigate known or anticipated conditions. The doorstopper requires the least volume of rock for a test and thus may be less sensitive to the effects of jointing and core diskings. The CSIRO triaxial cell can determine the complete (three dimensional) stress tensor from a single test. This represents a significant time and cost saving over the doorstopper and borehole deformation gage, both of which are biaxial devices requiring three separate tests in three noncoplanar boreholes for the same determination. However, the doorstopper and the CSIRO triaxial cell must be bonded to the rock by glue, and borehole conditions adverse to satisfactory bonding may be encountered. The borehole deformation gage has the advantage of requiring no glue, and, therefore, tests can be conducted more rapidly since the cure time is eliminated. However, the borehole deformation gage is sensitive to the presence of fractures and (or) core diskings. The end result is that no one overcoring cell is markedly superior to all other types for all conditions likely to be encountered in the Exploratory Shaft Facility. Versatility must be incorporated into the testing program as much as practicable to encompass the range of testing conditions possible in the Exploratory Shaft Facility. Instrument selection for a particular test will be based on experience and anticipated test conditions. As the Exploratory Shaft Facility testing program continues, it is anticipated that the expanding base of operational experience may lead to preferential selection of one type of cell.

In situ stress determination by overcoring assumes that the rock behaves in a linear elastic manner. While it is also common to assume isotropy, anisotropic behavior can be accounted for if necessary. Interpretation of the results from an individual overcore test must take into account the specific test performance and rock conditions to determine most likely values for in situ stress within the bounds provided by laboratory and in situ deformability parameters.

Excavation damage is anticipated to be limited to a relatively shallow depth of the immediate vicinity of underground openings. Determination of excavation induced stress by overcoring should therefore be possible within much of the zone of influence. Small flat jacks may be used to determine stress in the zone immediately adjacent to the opening. The feasibility of using the doorstopper in this zone will also be investigated, since it is possible to glue the cell to the rock face and thereby obtain data at the immediate boundary of the opening, providing rock damage does not interfere with the test.

8.3.2.2.3.1.2 Hydraulic fracturing.

The hydraulic fracturing test consists of isolating a short interval in a borehole with inflatable packers and injecting fluid (typically water) to fracture the rock. When the test interval is pressurized, the induced stress due to pressurization is superposed on the existing stress distribution about the borehole. As pressurization continues, the tangential stresses around the borehole wall are reduced until the rock at the borehole wall ruptures. Fracture initiation (breakdown) will occur when the pressure in the borehole is great enough to overcome the tangential stresses around the borehole and the in situ tensile strength of the rock. The fracture will initiate in the direction of least resistance, which is assumed to be perpendicular to the least principal stress in the plane perpendicular to the borehole.

After breakdown, pressurization is stopped to obtain values of the shut-in pressure. The shut-in pressure is defined as the pressure in the fracture just sufficient to hold the fracture open when the flow rate is zero. It is used to estimate the in situ stress perpendicular to the fracture, or the least horizontal principal stress. After the initial pressurization cycle, the test interval is repressurized for several cycles to obtain the pressure required to reopen the fracture and to obtain additional values of the shut-in pressure. The in situ tensile (rupture) strength of the rock is assumed to be equal to the breakdown pressure minus the fracture reopening pressure.

After completion of the pressurization cycles to initiate and extend the hydraulic fractures, an impression test is conducted to determine the orientation of the induced fracture. Impression tests also will be conducted in the test interval prior to the hydraulic fracturing test. These impressions are used to characterize the test interval and to provide a basis for comparison when the post-test impressions are examined. Impression tests use an inflatable packer with a thin layer of semicured rubber on the outer surface. This rubber liner conforms easily to the borehole wall when the packer is pressurized and retains an impression of the wall after deflation of

the packer. The orientation of the maximum horizontal in situ stress is taken as parallel to the orientation of the induced fractures. In addition to the impression test, the borehole televiewer may be used to investigate the test interval before and after fracturing.

Analysis of hydraulic fracturing data generally assumes that the borehole is parallel to a principal stress direction. While this assumption is usually valid for a vertical borehole (and can be later verified by correlative in situ stress determinations by overcoring in the Exploratory Shaft Facility), it is not necessarily true for horizontal and inclined holes. The test development program for hydraulic fracturing in the Exploratory Shaft Facility will include a review of hydraulic fracturing experience in horizontal and inclined holes, and modifications will be made to testing procedures and analysis methods as appropriate to obtain valid in situ stress determinations. Significant modification of equipment is not anticipated.

Another consideration in analysis of hydraulic fracturing data is the assumption of pore pressure values in determination of the maximum horizontal stress. This question will be addressed by means of a position paper regarding pore pressure assumptions, and by analysis of the hydraulic fracturing process as appropriate. Other factors to be considered in the application of hydraulic fracturing at the Hanford Site include the effects of preexisting joints or fractures in the test interval, the effects of noncircular holes (due to borehole spalling), and the possibility that the fractures may change orientation as they propagate away from the borehole wall.

8.3.2.2.3.1.3 Small flat jack testing.

Small flat jack tests are performed utilizing 0.6- by 0.6-m (2- by 2-ft) flat jacks installed in the walls or floor of the Exploratory Shaft Facility drifts. The term small flat jack is used to distinguish these tests from large flat jack tests, which utilize 0.6-by 1.2-m (2- by 4-ft) flat jacks for evaluation of rock mass deformational response.

The primary objective of the small flat jack test is to measure excavation-induced stress in the immediate vicinity of an opening. This test method is to be employed in the Exploratory Shaft Facility to determine tangential stress levels close to the surface of the underground excavation. The small flat jack test may be conducted in deep slots to obtain excavation-induced stress profiles in the vicinity of underground openings.

The test begins with installation of stress and deformation monitoring devices, followed by cutting a thin slot into the rock mass. Creation of the slot brings about a deformation of the rock into the slot and relieves stress perpendicular to the slot. A flat jack is then installed in the slot and pressurized until the stress relief resulting from the slot cutting is eliminated and deformation across the slot is restored to zero. The flat jack pressure at which the stresses return to the preslot level is commonly termed the "cancellation pressure." It is considered to be essentially equivalent to the in situ stress of the rock mass in the direction perpendicular to the plane of the flat jack.

A slot-cutting saw is being developed as part of the flat jack development program. One prototype design employs a diamond-impregnated chain saw concept to cut a slot closely matched in size to the flat jack dimensions. Other slot-cutting methods under consideration include the use of a water jet to cut the slot or drilling of overlapping holes. The latter method (successfully employed at the Near-Surface Test Facility) is the least desirable since it would require grouting the flat jacks in place, thus altering boundary conditions and complicating data analysis for deformability.

8.3.2.2.3.2 Thermal properties determination study

The thermal properties determination study consists of tests and analyses, conducted in the laboratory and in the Exploratory Shaft Facility, to determine thermal and thermomechanical properties of the host rock. Thermal and thermomechanical properties may vary within the host rock due to spatial variation, test scale, rock mass anisotropy, moisture content, intraflow structure, and fracture characteristics. Evaluation of test results will take the effect of these variables into account. Where a significant dependence is shown in the test results, the properties will be reported as a function of a particular variable. The properties to be determined through this study are thermal conductivity, specific heat, and thermal expansion coefficient. A detailed description of the study and of the tests and analyses to be performed is contained in the thermal properties determination study plan.

The primary tests and supporting tests and analyses presently being considered for inclusion in the study are shown in Table 8.3.2.2-5. The table also includes reference to the pertinent performance issues and design elements requiring the parameters to be determined through the study. Supporting tests and analyses shown in the table will not be used to determine thermal properties directly, but are proposed elements of the study that enhance the determination of methods shown.

The possibility of spatial variation of properties must be accounted for in evaluations of in situ and laboratory test data. Variability is expected to result from differences in rock texture and jointing. Test scale may affect the results obtained, since most thermal properties tests typically respond to the average value of the property over the volume of rock under investigation, which is a function of the test scale and geometry. With increasing-size test scale, the effects of individual discontinuities may become less important, and the effects of lateral variability on the rock mass may become more important. Laboratory test specimens will be obtained from several different surface boreholes around the reference repository location, and in situ tests will be performed in several locations at the Exploratory Shaft Facility to evaluate spatial variation of thermal and thermomechanical properties.

Table 8.3.2.2-5. Thermal properties tests, studies, and supporting analyses

Investigation	Study	Performance issues	Design issues	Parameter	Primary tests	Supporting tests and analyses
Geomechanical characteristics of the host rock	Thermal properties determination	1.1	1.11	Thermal conductivity	Laboratory (comparator)	Full-scale heater test
		1.4	1.12		Field (thermal conductivity probe)	Damaged rock characterization
		1.5	2.7	Heat capacity	Laboratory (calorimeter)	Borehole geophysics
		1.8	4.2		Field (thermal conductivity probe)	Full-scale heater test
		2.4		Thermal expansion coefficient	Laboratory (dilatometer)	Borehole geophysics
					In situ expansion test	Damaged rock characterization

PST87-2005-8.3.2-16

Test samples to examine spacial variability within the Cohasset flow will be taken from all cored boreholes within a 10 km (6.2 mi) radius of the center of the reference repository location. Existing data have been collected from three holes within the reference repository location. Additional tests will be conducted on core from nine holes, two of which remain to be drilled. Because of the relatively consistent results obtained to date, a wide variation in data is not anticipated, and the number of holes scheduled for testing is considered adequate at present. Statistical analyses will be performed when the scheduled tests have been performed to determine the sufficiency of the data to estimate spacial variability.

Anisotropy may significantly affect determinations of thermal conductivity and thermal expansion coefficient. Some mineral and rock materials exhibit a high degree of anisotropy for thermal conductivity and thermal expansion. Anisotropy in the host rock is not expected at intact scale, but may be present at rock mass scale if jointing in the rock shows preferred orientation. An example of preferred orientation is the primarily vertical fractures present in columnar basalt. Effects of anisotropy will be determined by tests in the laboratory on oriented core and specimens with oriented fractures obtained from surface and Exploratory Shaft Facility boreholes. Oriented tests also will be performed in the Exploratory Shaft Facility at rock mass scale.

Moisture within the volume of rock under investigation can have a major effect on determinations of the thermal conductivity or heat capacity of the rock mass. Water has a heat capacity approximately four times that of basalt. Water also has a relatively high rate of vaporization, and a boiling point within the anticipated design temperature range in the repository environment. To the extent that the water is free to move within the rock mass, heat transport by thermal convection may significantly affect thermal conductivity and heat capacity measurements. Moisture effects in laboratory tests will be evaluated by comparing test results to sample moisture content, and by successive test cycles. An understanding of the relationship of structurally bonded moisture and temperature with thermal properties will be supported by laboratory thermogravimetric analyses. There are presently no plans to control moisture content in laboratory tests, although the feasibility of this is under investigation. There is no feasible method known at this time to control sample moisture content in the field.

Thermal and thermomechanical properties are expected to vary with variations in intraflow structure because these subdivisions are based on observable changes in physical properties, lithology, texture, and overall rock quality. Laboratory tests will be conducted on specimens from each intraflow unit accessible from surface boreholes or boreholes from the Exploratory Shaft Facility to determine properties of these units. Because of access constraints, rock mass scale tests are not likely to be possible in various intraflow structures.

Fracture characteristics might have an effect on the in situ thermal properties of the rock mass. Thermal properties of the fracture-filling material can be significantly different from that of the rock matrix, with the result that the thermal properties over the volume of rock under investigation can be affected by fracture spacing and by fracture characteristics. Fractures also provide pore space and conduits for water. The presence of fractures may significantly alter the temperature and (or) stress distributions, and may control rock deformation on a local scale. The primary method of examining fracture characteristics will be through laboratory determination of the thermal properties of intact core and of fracture-infilling materials to estimate the rock mass scale properties. In situ tests conducted at the Near-Surface Test Facility, as well as the tight nature of the joints observed in the core from the Cohasset flow at depth (refer to Chapter 2), indicate that laboratory results from intact core adequately represent in situ thermal properties in basalt with tight jointing. In situ testing in the Exploratory Shaft Facility will be performed to verify extrapolation of rock mass properties from laboratory findings.

Primary thermal properties test descriptions are provided in Sections 8.3.2.2.3.2.1 through 8.3.2.2.3.2.3.

8.3.2.2.3.2.1 Thermal conductivity.

The comparator test for thermal conductivity is performed by placing a sample of the basalt in intimate, end-to-end contact between two reference samples. A heater applies a temperature-controlled quantity of heat to the top reference sample. As the heat flows across the length of the top reference, the induced temperature gradient is measured by thermocouples. The heat continues to flow across the test specimen and through the bottom reference sample. Radial heat loss from the test setup is prevented by insulation surrounded by a guard heater. Temperature gradients across the specimen and the bottom reference are measured. Knowing the thermal conductivity coefficients and dimensions of the top and bottom reference samples, the heat flow in the reference samples may be calculated. The heat flow across the test specimen is calculated as the average of the heat flow across the top and bottom reference. The thermal conductivity of the test specimen is then computed from the specimen dimensions and the heat flow through the specimen. During the development stage, variables such as moisture content, heating rate, and the influence of a single joint on heat capacity will be assessed.

The thermal conductivity probe is a long, cylindrical heater that is placed in a borehole and surrounded by a heat transfer fluid. With the probe and borehole initially at ambient temperature, constant power is supplied to the probe, and the resulting temperature rise at the rock/probe interface is monitored. After an initial nonlinear period, the thermal conductivity probe test yields a relatively linear plot of temperature increase as a function of the natural log of time. Knowledge of both the power supplied to the probe and the resulting temperature rise at the surface of the probe as a function of the natural log of time can be used to determine the thermal conductivity of the surrounding rock. Hydrology and geochemistry may affect test results. These effects will be considered as test variables.

8.3.2.2.3.2.2 Heat capacity.

A heat capacity test will be performed in the laboratory with an adiabatic calorimeter. The calorimeter consists of the calorimeter vessel and the adiabatic shield. Ideally, the adiabatic shield is maintained at the same temperature as the calorimeter vessel so there is no temperature differential, thereby creating an adiabatic condition, with no heat exchange between the calorimeter and the surroundings. The intermittent heating method will be employed to measure heat capacity. The calorimeter vessel and the adiabatic shield are heated with the times recorded at which selected temperatures are reached. The energy input is determined by concurrent measurements of time and power input to the heaters. Dividing this energy by the temperature rise gives the average heat capacity of the calorimeter plus the sample. The average heat capacity of the sample is then obtained by subtracting the experimentally determined heat capacity of the empty calorimeter.

Heat capacity of the rock mass may be determined by two methods using data generated in a thermal conductivity probe test. The first method involves an iterative calculation of heat capacity using temperature and time data from the standard thermal conductivity probe test. The second method alternatively, by measuring temperatures at various radial distances from the heater centerline, can obtain the heat capacity by matching computed and actual temperature profile data where the computed profiles were generated by varying thermal diffusivity values. On determination of an adequate curve match, the appropriate thermal diffusivity value can be used to back calculate the heat capacity.

8.3.2.2.3.2.3 Thermal expansion coefficient.

The thermal expansion coefficient of basalt will be measured in the laboratory in accordance with the American Society for Testing Materials' standard E-228-71, Thermal Expansion by Vitreous Silica Dilatometer (ASTM, 1986c). In this method, a specimen is placed in a vitreous silica tube holder in contact with a freely suspended vitreous silica probe rod. The probe rod is connected to the core of a linear variable differential transformer that measures sample dilation. The sample is heated in a tube furnace that controls the temperature by a microprocessor-based process programmer. A thermocouple is placed in contact with the sample and connected to a temperature indicator. The temperature indicator and displacement measuring device give continuous data on length change versus temperature.

Instantaneous thermal expansion coefficients are computed from the specimen length and a series of temperatures and associated expansion values taken over the full temperature range of the test. The data points must be corrected for expansion of the system with a system correction factor that is determined by conducting expansion tests on standard reference materials.

Confirmation of thermal expansion coefficient in situ will be supported by the full-scale heater tests and heated block test. The feasibility of developing an alternative method of determining the in situ thermal expansion

coefficient will be evaluated. A method capable of producing in situ results quickly, easily, and cost effectively is sought. Current alternative concepts for evaluation include streamlined versions (i.e., smaller scale and less instrumentation) of the full-scale heater and heated block tests.

8.3.2.2.3.3 Mechanical properties study

The mechanical properties determination study consists of tests and analyses to be conducted in the laboratory and in the Exploratory Shaft Facility to characterize the mechanical properties of the repository host rock. The objective of this study is to provide quantitative description of the host rock properties as required to resolve key issues identified through repository design, performance assessment, and other studies. The properties to be determined include deformability, strength, and physical properties of the parent rock material and discontinuities (joints).

The primary tests and supporting tests and analyses being considered for inclusion in the study are shown in Table 8.3.2.2-6. The table also includes reference to the pertinent performance issues and design issues requiring the parameters to be determined through the study. Supporting tests and analyses shown in the table will not be used to determine mechanical properties directly, but are proposed elements of the study that enhance the determination of methods shown. A detailed description of the tests and analyses to be performed is contained in the mechanical properties determination study plan.

Mechanical properties will vary within the host rock flow because of scale effects, intraflow structure, lateral variability, anisotropy, temperature, time dependence, fracture characteristics, and moisture. Determination of mechanical properties at rock mass scale would be preferred, since the combined effects of these variables are intrinsically factored into large-scale measurements. However, most functional dependencies involving mechanical properties will be investigated primarily at the laboratory scale because of the operational constraints inherent in large-scale in situ tests. Large-scale tests will be conducted in the Exploratory Shaft Facility as practical to confirm these dependencies. This section presents a brief description of the study with regard to the variables discussed above. Lateral variabilities of certain mechanical rock properties will be assessed in situ through borehole geophysical methods. Point-by-point profiles of bulk density, porosity, and acoustic/elastic properties will be provided, with good spatial resolution, by borehole geophysical logs. Variations of acoustic/elastic and electrical properties within large blocks will be mapped through tomographic analyses of cross-hole seismic and cross-hole radar data.

Table 8.3.2.2-6. Mechanical properties tests, studies, and supporting analyses

Investigation	Study	Performance issues	Design issues	Parameter	Primary tests	Supporting tests and analyses
Geomechanical characteristics of the host rock	Mechanical properties determination	1.4	1.11	Deformability	Uniaxial compression	Small flat jack tests
		1.5	1.12		Triaxial compression	Biaxial cell tests
		1.8	2.7		Borehole jack	Sonic velocity
		2.4	4.2		Plate bearing	Borehole sonic methods
					In situ block test	Mine-by test
					Cross-hole seismic	Constitutive modeling
					Laboratory creep tests	Study of scale effects
						Structural geology
						Rock mass classification
						Study of temperature
						Effects of discontinuities
				Strength	Uniaxial compression	Mine-by test
					Triaxial compression	Constitutive modeling
					Rock mass triaxial*	Study of scale effects
					Block shear*	Full-scale heater test
						Structural geology
						Rock mass classification
						Empirical methods
				Joint properties	Direct shear (core)	Mine-by test
					Direct shear (bench scale)	Hydrologic studies
					Triaxial shear	Constitutive modeling
					Block shear	Study of scale effects

*Test is still under evaluation.

PST87-2005-8.3.2-17

In the laboratory, intact specimen strength and joint shear strength test results typically exhibit some degree of dependence between strength and specimen size. For large samples (containing one or more natural fractures), there is a transition range up to a size with a sufficient number of joints such that the sample's response is a representative measure of the rock mass. In context, three sample size ranges of interest can be defined: (1) intact scale, (2) rock mass scale, and (3) multifractured sample taken from a single column (i.e., does not contain column-forming joints). There are plans for evaluating as many independent variables as feasible in tests conducted in situ at the rock mass scale and in the laboratory on multijointed samples. All of the variables discussed above will be investigated in the laboratory. For some properties, such as strength and time-dependent behavior, it is likely that testing will be feasible at the laboratory scale only.

Samples from surface boreholes will be used to conduct a systematic examination in the laboratory of variations in intact mechanical properties between intraflow structures of the host flow (i.e., to assess the vertical variability of mechanical properties within the flow). Sampling will be conducted in a manner that should additionally enable an assessment to be made whether significant differences in mechanical properties may exist between different intraflow structures of one kind (e.g., two entablature units or two vesicular zones) within the host flow. A limited number of deformability tests will be performed in a vesicular zone near the Exploratory Shaft Facility horizon. This would provide some basis for comparing large-scale mechanical properties measurements for vesicular and dense interior zones.

Mechanical properties may vary from one location to another within a specified intraflow structure. Considering the number of applications for mechanical properties, a finding that one or more properties exhibits a significant degree of lateral variability could have important implications. If it is established that mechanical properties vary significantly from point to point within the host flow with respect to design compliance, it would be necessary to increase the scope of the study to characterize the affected properties in detail. Conversely, if it were found that design compliance is not sensitive to lateral variation, the scope of this study could be reduced.

Test samples to examine spacial variability within the Cohasset flow will be taken from all cored boreholes within a 10-km (6.2-mi) radius of the center of the reference repository location. Existing data have been collected from three holes within the reference repository location. Additional tests will be conducted on core from nine holes, two of which remain to be drilled. Because of the relatively consistent results obtained to date, a wide variation in data is not anticipated, and the number of holes currently scheduled for testing is considered adequate at present. Statistical analyses will be performed when the scheduled tests have been performed to determine the sufficiency of the data to estimate spacial variability. Initial assessment of lateral variability will be made at the laboratory scale. The number and location of in situ tests in the Exploratory Shaft Facility will be based on the results of this assessment.

Plans for testing at the laboratory scale are based on the assumption that basalt behaves isotropically at the intact scale. At the rock mass scale, anisotropy in mechanical properties is anticipated, primarily because of the preferential structural characteristics of basalt. Investigation of anisotropy at the rock mass scale will be an essential aspect of planning, design and analysis of in situ tests. Tests incorporating a means of loading in two or more directions, and oriented test setups are planned for the Exploratory Shaft Facility. Simple, portable in situ test techniques such as borehole jacking may be employed as a means of indexing rock mass deformability in oriented boreholes and determining spacial variability.

The temperature dependency of strength and deformability parameters will be investigated principally at the laboratory scale. Beyond strength and deformability testing, there is a need to determine whether basalt will exhibit any tendency to creep at elevated temperatures. Constitutive relations are required as inputs to numerical modeling to simulate the response of the rock mass to heating. The feasibility of constructing an in situ test to investigate temperature dependencies at the rock mass scale is currently being investigated.

Time-dependent behavior of intact basalt and single-jointed specimens will be investigated in the laboratory. It is anticipated that time-dependent behavior will be detectable in fracture fillings at much lower load levels than in intact specimens. Time-dependent behavior at the rock mass scale will be investigated in the rock support and deformation monitoring program that is part of the opening performance study (Section 8.3.2.2.3.4). The primary reasons for evaluating time-dependent behavior of basalt arise from the long timeframes identified in repository performance requirements and the fact that very little information exists concerning time-dependent phenomena in basalt. Creep deformation of intact basalt (if it is demonstrable at all) it is not anticipated to be a major design and performance consideration.

To characterize the mechanical properties of joints, single-jointed specimens will be tested in direct shear and triaxial shear at laboratory scale, bench scale, and possibly the rock mass scale. Joint roughness, aperture, and infilling type are the specific characteristics to be quantified. Shear strength and shear and normal stiffnesses will be measured. The feasibility of conducting an in situ test will be explored in the event that one or more classes of fractures are observed in the Exploratory Shaft Facility that are not amenable to characterization at a smaller scale. Joint shear strength can be described in terms of the normal stress across the fracture surface, a frictional resistance factor attributable to the surface condition, and the initial cohesion (if any) of the bond between the opposed surfaces. Fracture roughness will be characterized with changes in scale. Large-scale roughness (or waviness) consists of undulations on joint surfaces with associated periodicity that may vary from less than 1 cm (0.4 in.) to more than 1 m (3.2 ft). Small-scale roughness (unevenness) refers to the individual asperities on joint surfaces corresponding to crystal, grain, or inclusion boundaries. Asperities tend to be ground off during shear displacement, whereas undulations tend to induce joint dilation because they are too large to shear through.

For all fracture-infilling types (but especially clays), there is a need to establish how mechanical properties measured on dry specimens in the laboratory are to be related to the in situ moisture condition. Samples can be tested dry and saturated by either the direct shear or the triaxial shear technique. An ideal approach for constraining moisture effects would be to test all samples at in situ moisture content. However, this option is not available in practice since the current core inventory exists in an "air dry" condition.

Primary mechanical properties test descriptions are provided in Sections 8.3.2.2.3.3.1 through 8.3.2.2.3.3.12.

8.3.2.2.3.3.1 Uniaxial compressive strength.

Uniaxial (or unconfined) compressive strength is a measure of a material's strength under conditions where the specimen is loaded axially but is not confined externally. The uniaxial compressive strength test is a conventional test method for rock strength determination. A cylindrical specimen is placed within the confines of a loading device and loaded until specimen failure occurs. Maximum load and specimen diameter are used to calculate the uniaxial compressive strength. During these tests, it is common practice to measure axial and circumferential strains on specimens for determination of the material's elastic properties (e.g., Young's modulus and Poisson's ratio).

8.3.2.2.3.3.2 Triaxial compressive strength.

Triaxial (or confined) compressive strength is a measure of a material's strength under conditions where the specimen is axially loaded and laterally confined. During the triaxial compressive strength, it is common to measure axial and circumferential strains on specimens for determination of the specimen's elastic properties. In the BWIP rock mechanics laboratory, this test is performed per a procedure based on the American Society for Testing Materials' standards for triaxial compressive strength of undrained rock core specimens with pore pressure measurements (ASTM D-2664-86) (ASTM, 1986d) and elastic moduli of intact rock core specimens in uniaxial compression (ASTM D-3148-86) (ASTM, 1986b). In the triaxial compressive strength test, a prepared cylindrical specimen is placed inside a triaxial cell that is inserted into a load frame device. Hydraulic pressure is applied to the specimen to develop a specified confining pressure, and the specimen is loaded axially until failure occurs. The load at failure and the specimen diameter are used to calculate the triaxial compressive strength at the test confining pressure. The BWIP laboratory has facilities to run triaxial compressive strength tests at elevated temperatures. Tests are planned at ambient and elevated temperatures under dry and saturated conditions, and under elevated and drained pore pressure conditions.

8.3.2.2.3.3.3 Ultrasonic pulse testing.

The ultrasonic pulse test, also called the sonic wave velocity test, is a nondestructive method for determining propagation velocities of elastic waves in laboratory intact rock specimens. The measured velocities are used, in turn, to calculate dynamic elastic properties for the specimen (Young's modulus, shear modulus, Poisson's ratio, and bulk modulus). In the BWIP rock mechanics laboratory, the ultrasonic pulse test is performed on all mechanical properties specimens as a routine aspect of sample characterization. Testing conforms to TOP LT-TL-759. This procedure was prepared based on the ISRM suggested method for the test (ISRM, 1981) and the ASTM standard (ASTM D-2845-83 (ASTM, 1986)).

8.3.2.2.3.3.4 Borehole jacking.

The borehole jacking test is an in situ test used to assess the deformability of the rock mass. The borehole jacking test is performed by installing a radial jacking device with circumferential bearing platens in a borehole and pressurizing the walls of the borehole in an incremental sequence of loading and unloading. The diametral or volumetric displacements that result at each pressure level are measured. A stress and deformation relationship is then developed from the data to assess the deformation characteristics of the rock, nonrecoverable strain (hysteresis) observed after unloading. The borehole jacking tests can be used to describe the deformation characteristics and extent of the damaged rock zone normally found around underground excavations, as well as remote undisturbed rock.

The borehole jacking test is a small-scale test and, therefore, the modulus of deformation calculated from the test data is not considered to be representative of the rock mass. Consideration will be given to using the borehole jacking test as an index test in the Exploratory Shaft Facility testing program, because the test is simple to perform and can be performed at any desired depth or location. Thus, numerous tests can be conducted to assess the spatial variability of the modulus.

8.3.2.2.3.3.5 Plate bearing.

The plate bearing test is an in situ test designed to evaluate the deformability of the rock mass at ambient temperature and is commonly used for rock mass characterization in large underground construction projects. In the plate bearing test, loads are applied to the surfaces of an underground opening and the resulting rock displacements are measured. Analytical methods based on the theory of elasticity are then used to calculate the modulus of deformation from the stress and displacement data. The plate bearing tests are used primarily to describe the deformational characteristics of the excavation-induced damaged rock zones normally found around underground openings. However, depending on the load attenuation characteristics, the plate bearing test may provide deformational information for less damaged rock.

In the plate bearing test, the rock mass is stressed by simultaneously loading opposite and parallel surfaces of a drift using a jacking device that spans the diameter of the opening and transfers the load to the rock by the bearing plates. A pressurization cycle consists of an incremental sequence of loading and unloading. Several cycles, each having a successively higher magnitude, are typically used until the maximum pressure of the test is reached. Resulting rock displacements are measured at each load increment in the direction parallel to the loading axis using deformation instrumentation. Suggested methods for conducting the plate bearing test are provided by the International Society of Rock Mechanics and the U.S. Bureau of Reclamation.

8.3.2.2.3.3.6 Block test.

The block test is an in situ test designed to evaluate the deformational behavior generated by mechanical and thermal loading of a representative rock volume under controlled stress boundary conditions. This test is designed to measure deformational response of the rock mass beyond the excavation-induced damaged rock zone, whereas the plate bearing test (as described in the previous section) will provide deformational information primarily within the excavation-induced damaged rock zone.

The test consists of a large-scale geomechanical rock mass model that is isolated on five sides from the surrounding rock and the in situ stress field. Four slots are cut in the drift wall or floor to isolate the test block and provide space for the mechanical loading devices. The method employed for slot excavations should be designed to impart minimal disturbance beyond the slot surfaces. Flat jacks are inserted into the slots to apply pressure to the sides of the test block for biaxial loading. Either cable jacks with tendons installed through and grouted beyond the testing zone or a plate-bearing type apparatus can be used to apply loads to the block face to produce triaxial loading conditions. This loading configuration allows the block to be loaded simultaneously in three orthogonal directions. Electric heaters installed in boreholes located within and around the test block can be used to elevate rock temperatures uniformly or nonuniformly to induce thermal stresses in the rock mass. Heaters and jack-loading systems can be activated individually or simultaneously to evaluate coupled thermomechanical effects on the test block.

The response of the test block from thermal and (or) mechanical loading is monitored by instrumentation installed in boreholes located within and along the periphery of the block. These instruments are designed to measure displacement, stress, strain, and (or) temperature within the test zone.

A typical test procedure would include cyclic mechanical loading and unloading of the test block in all three principal directions at ambient and stabilized elevated temperature levels, and at varying confining stress levels. Loading conditions (uniaxial, biaxial, triaxial, and hydrostatic) can be manipulated during testing. Loading stresses applied to the block could be varied from 0 to 41 MPa (6,000 lbf/in²). Borehole heaters allow the

temperature of the test block to be regulated between ambient and 300 °C. Groundwater in the test environment may affect the mechanical and thermal response of the block test. Groundwater effects will be considered in the interpretation of results.

8.3.2.2.3.3.7 Cross-hole seismic testing.

The cross-hole seismic test is a pulse transmission technique employing a highly reproducible source with a receiver in another borehole for investigating the rock mass between the holes. The method uses the entire P- and S-waveform, velocity, and attenuation to evaluate anomalies. Applications of the cross-hole seismic test for the Exploratory Shaft Facility include (1) the correlation of dynamic and static rock modulus determinations, (2) the determination of the degree and depth of rock degradation around tunnels due to the excavation, and (3) the monitoring of thermal effects in the rock mass during heater test. Tomographic methods will be considered and evaluated for the analysis of cross-hole seismic data.

Data are typically observed on an oscilloscope and recorded on magnetic tape (preferably digital). Both transmitting and receiving sondes must have provisions for providing good, reproducible rock-transducer coupling. This is usually accomplished through hydraulically activated reaction arms that extend against the borehole wall. Additionally, the acoustic impedance mismatch between the transducer and the rock should be minimized.

The source transducers are usually driven by a pulse generator and the received waveforms may be stacked. To greatly enhance the signal-to-noise ratio, a variety of waveforms may be employed including a pseudorandom binary sequence for pulse compression.

8.3.2.2.3.3.8 Rock mass strength testing.

Rock mass strength testing is designed to assess the compressive and shear strength of rock in situ by loading a large sample of rock containing a representative number of fractures to failure. The rock mass strength test program is at the feasibility and early conceptual design stage. A degree of uncertainty exists for the program's success, which is dependent on the ability to (1) develop loads that are sufficient to produce failure (particularly under confining conditions), (2) excavate large test samples, and (3) instrument the test to characterize the failure process. Studies are planned to evaluate existing rock mass strength testing techniques, specimen size needs, load levels required to produce failure in large basalt samples, sample excavation techniques, and instrumentation needs.

The majority of rock mass strength tests reported in the literature has been large-scale unconfined tests (e.g., pillar tests) in weak rock and direct shear tests on discontinuities. The usefulness of unconfined tests are limited relative to triaxial tests where a failure criterion for the rock mass can be developed. On the other hand, confining tests are more complex and

success becomes more questionable in hard rock like basalt, because a rapid increase in strength is expected with confinement. However, recent advances evolving from the BWIP flat jack development program have increased the likelihood of achieving loads necessary to produce failure.

Two testing concepts tentatively proposed to measure the triaxial compressive and shear strength of large basalt samples are the rock mass triaxial and block shear tests, respectively. Conceptually, the rock mass triaxial test is similar to the classical laboratory test on intact rock where, with the exception of the base, a large cylinder of rock is isolated from the rock mass on all sides. Flat jacks may be used to apply confining and axial loads to the cylinder. A potential alternative method would be to remove the large rock cylinders for testing under laboratory conditions. The block shear test, as conceived, would apply shear loads using flat jacks to a large block of basalt subjected to normal loads. The block shear test would be similar to that described by the International Society for Rock Mechanics (Brown, 1981). In addition, rock mass strength will be assessed from observations and measurements taken during the rock support and deformation study, and through back analysis of the mine-by test.

8.3.2.2.3.3.9 Direct shear strength (rock core).

The purpose of the direct shear test is to determine the peak and residual shear strength along a fracture as a function of the normal stress applied across its plane. The test specimen is encapsulated in the two halves of the shear box using a potting compound (e.g., hydrostone, plaster of paris). The shear box then is placed in the loading frame and instrumented to record normal and shear loads and displacements. A normal stress is applied to the specimen and then the shear load is applied gradually until failure occurs. After failure, the specimen is sheared continuously until the rise or fall in shear stress ceases to occur for increasing shear displacement. Successive tests are conducted at varying normal stresses. Joint geochemistry will be determined during sample characterization to assess its potential impact on the test results.

8.3.2.2.3.3.10 Direct shear strength (bench scale).

The purpose of this test is to measure joint parameters for discontinuities that exhibit properties not adequately sampled in direct shear tests on 7.62-cm (3.0-in.) cores (NX-size) because of their variations due to scale.

The objectives of this test are to characterize the mechanical properties of column-defining and column-dividing joints by testing multifractured samples and to estimate the strength and deformability of still larger discontinuities (i.e., tectonic fractures encountered).

Except for their size and capacity, the items of apparatus used to perform the bench-scale direct shear test are the same as those mentioned for the conventional direct shear test. The procedure would be generally the same as for the direct shear test on core.

A major constraint for this test is the limitation on the stress levels that can be applied to large specimens. A preliminary survey of subcontractors and vendors has revealed that the largest available direct shear machine can accommodate specimens with joint surface areas of about $2,065 \text{ cm}^2$ (320 in^2). Tests on specimens of these dimensions would be limited to normal stress levels of about 3.45 MPa (500 lbf/in^2).

8.3.2.2.3.3.11 Triaxial shear strength.

The purpose of the triaxial shear test is to provide shear strength data from single-joint core specimens at stresses above the levels that are obtainable in laboratory direct shear or in situ test methods. This test method also can be used to estimate joint shear and normal stiffness properties.

The triaxial shear test is intended to determine the frictional properties of a single joint contained in a cylindrical rock specimen. The joint should be oriented at an angle of 30° to 45° with the core axis of the specimen to ensure that joint slip occurs. The specimen is placed in a triaxial cell and loaded axially after confining pressure has been applied. To maintain constant joint normal stress during the test, confinement must be adjusted as the vertical stress is increased. Joint geochemistry will be determined during sample characterization and an attempt will be made to assess its effect on the triaxial shear strength results.

8.3.2.2.3.3.12 Creep testing.

This section reflects the current thinking of the BWIP about a strategy for quantifying long-term behavior of the rock mass, which is a primary concern in the design of waste packages to provide containment for 300 to 1,000 yr. The term "creep" broadly refers to deformation of the rock mass after its initial instantaneous response to loading. This could include growth of microfractures in intact basalt upon heating or as a result of sustained stresses or time-dependent slip along joint surfaces. Shear and normal displacement along discontinuities are expected to be the predominant mode of time-dependent deformation, but the long-term response of intact basalt may be important because of the interlocking nature of the rock mass.

A detailed testing program for measuring time-dependent responses of the rock mass to excavation and thermally induced loads has not been formulated at this time. Some techniques that may be applicable for evaluating creep in basalt include evaluation of case histories of deep mines and tunneling projects, in situ measurements, study of geologic analogies, and parametric sensitivity analyses using (1) a range of assumed constant strain rates and (2) published constitutive models for other hard, brittle rock types such as granite. Application of these types of methods will provide insight into the need for consideration of rock mass creep in repository design and performance assessment and may lead to laboratory creep testing of intact rock, of individual joints, and of representative assemblages of blocks. Temperature, pore pressure, scale, loading, constitutive model formulation, rate effects, and discontinuity infilling geochemistry will be considered in the definition of a laboratory testing program.

The BWIP hopes to use in situ measurements made during rock support and deformation monitoring (Section 8.3.2.2.3.4.1) to provide an indication of time-dependent deformation of the rock mass around prototypical repository openings. The feasibility of obtaining measurements over a relatively short time period that will provide meaningful data for long-term stability assessments is unknown at this time.

8.3.2.2.3.4 Opening performance study

The purpose of this study is to characterize the performance and stability of openings in the Exploratory Shaft Facility. The study is essentially concerned with characterizing the host rock environment under postsubsurface excavation/pre-waste-emplacement and post-waste-emplacement conditions. The objectives of the study are to provide the following data:

- Deformational, thermal, and thermomechanical response data for repository prototypic underground openings.
- Performance data on repository prototypic rock support systems.
- Mechanical characteristics data of damaged rock around prototypic openings.

The primary test methods under consideration for inclusion in the study are shown in Table 8.3.2.2-7. Also shown in Table 8.3.2.2-7 are the tests and analyses that indirectly support the evaluation of opening performance and stability. A detailed description of the tests and analyses to be performed is contained in the evaluation of opening performance and stability study.

The opening performance study will be an ongoing effort throughout the construction and operation of the Exploratory Shaft Facility to provide data for characterizing the expected response of the host rock during and after repository construction and after waste emplacement. In particular, information will be collected to determine the excavation-induced and temperature-induced effects on the host rock.

The major use for the information gathered and interpreted from the opening performance study will be in the development and validation of the comprehensive set of models used to characterize the behavior of the basalt rock mass during and after repository construction and after waste emplacement. These models may include empirical, physical, mathematical, and numerical idealizations of repository components that are used in the design, construction, and performance assessment of the repository system. The prototypic nature of the principal elements of this study (with regard to expected repository conditions) should allow direct application of the information generated to the model development, validation, or analysis studies. The development and validation of repository design models are described in Section 8.3.2.5.

Table 8.3.2.2-7. Opening performance tests, studies, and supporting analyses

Investigation	Study	Performance issues	Design issues	Parameter	Primary tests	Supporting tests and analyses
Geomechanical characteristics of the host rock	Evaluation of opening performance	2.3	1.11 2.7 4.2	Opening performance	Rock support/deformation monitoring test Mine-by test Full-scale heater test Room-scale heater test	Large flat jack test Small flat jack test Overcoring test Plate bearing test Borehole jacking test Block shear test Cross hole seismic test In situ thermal expansion test Thermal conductivity probe test Rock mass classification Geophysics tests: • Ground probing radar • Seismic refraction • Gamma density log • Resistivity log • Sonic pulse • Blast vibration monitoring • Acoustic emissions Damaged rock characterization Study of scale effects In situ triaxial test Heated block test

PST87-2005-8.3.2-8

Information derived from the opening performance and stability study will be used to estimate the currently unknown or randomly variable factors that affect the rock mass. An understanding of these factors is necessary for any definitive analyses of the repository system. Areas that will be investigated in this study include the following:

- Assessment of deformational and failure mechanisms that influence and control opening response.
- Validation of thermal and thermomechanical properties of the rock mass.
- Spatial variation of rock properties.
- Influence of various geologic conditions and structures of the opening response.
- Interaction of support systems with the rock mass.
- Influence of construction methodology on opening response and performance.

Quantifying the mechanisms that control the rock deformational response may be one of the most difficult tasks in developing a comprehensive model of the repository system due to the complex and heterogeneous nature of closely jointed basalt. The overall response is comprised of phenomena occurring at a variety of scales including that of the intact rock, an individual joint, up to the rock mass scale. The information derived from tests and analyses at each of these scales will provide data on the components of the constitutive relationships governing rock mass behavior. Additionally, the spatial variation of various geologic features and the extent and characteristics of damaged rock around an opening must be evaluated in the development of a comprehensive conceptual model of rock mass behavior. The results from the opening performance and stability study will provide data that include the influence of all the component behavioral modes for validation of models employing these constitutive relationships.

Typically, in the design of underground openings, the influence of geologic conditions, rock support systems, and construction methodology are assessed through empirical means based on experience with similar situations. In the design of a nuclear waste repository, empirical methods will contribute significantly to these areas; however, the need for definitive design validation and performance assessment will require the design basis to be quantified based on actual measurements performed under prototypic conditions. Modification and (or) validation of the empirical methods used to design the rock support systems and construction methodology will be the second major use of the information derived from the opening performance and stability study. Information on the geologic conditions throughout the Exploratory Shaft Facility will be compared with the performance of the the construction methods, the observed response of rock support systems, and opening deformation monitoring to integrate the effects of these factors. Additionally, the

design of a nuclear waste repository will include two requirements not normally considered in underground design: (1) the requirement for retrievability of waste canisters for a specified time period and (2) the need to seal all penetrations and boreholes. These two considerations further increase the need for a quantified understanding of the rock mass characteristics because of the limited available precedent in analyzing and modeling such phenomena.

Several of the aspects of rock behavior discussed above (e.g., deformational response, geologic conditions, rock support system) will be influenced to some degree by thermal loading. Data will be generated to quantify the effects of heating on rock mass properties and opening performance for development and validation of the thermal and thermomechanical components of the design analyses and models. Prototypic observation of the thermal and thermomechanical response are critical to repository design because of the lack of previous experience in the mining and construction industries with the imposed elevated temperature fields on underground structures. Waste package design also will require information on the thermal and thermomechanical characteristics of the rock mass in the vicinity of the emplacement borehole to provide the basis for evaluation of the maximum temperature and stress conditions that can be expected.

Primary opening performance test descriptions are provided in Sections 8.3.2.2.3.4.1 through 8.3.2.2.3.4.4.

8.3.2.2.3.4.1 Rock support/deformation monitoring.

The purpose of the rock support/deformation monitoring program is to characterize the post-excavation host rock conditions that will be important for (1) relating changes with the construction operations to the resulting rock conditions, (2) selecting test sites, and (3) evaluating test results throughout the Exploratory Shaft Facility. The pre-excavation host rock conditions will change due to the construction activities. During Exploratory Shaft Facility excavation and ground support installation, the rock mass around openings will deform in response to the changing stress field. Rock mass deformation will continue until equilibrium is established between the rock mass support system and the stress field.

Rock support/deformation monitoring is an extensive program to characterize the excavation-induced changes to the rock mass throughout the Exploratory Shaft Facility. Information will be gathered to evaluate the relationships between the construction process and the rock mass response. Data will be analyzed specifically to evaluate rock mass response differences due to excavation and support parameters, rock mass conditions, intersection geometry, drift size, and opening orientation in the Exploratory Shaft Facility. Data gathering will begin during breakout from the shaft and continue throughout the construction activities and the remaining life of the facility.

Data from the monitoring program will be obtained to characterize the excavation and support operations, classify the exposed rock mass, evaluate spacial variability, and document changes over time. Geologic mapping and borehole geophysical information will be used to classify the rock mass. Tunnel inspections will document the location of water inflow, support system deterioration, and local rock mass instabilities. Areas of rock mass instability may indicate zones of relative high stress conditions or low rock mass strength. Rock mass response data will include (1) deformation measurements from convergence gages and borehole extensometers; (2) hydrologic measurements from inflow monitoring, pore pressure measurement, and injection tests; (3) stress determinations (absolute and stress change) by overcoring, small flat jacks, and stress gages; and (4) support system loading information from load cells and strain gage rock bolts.

Monitoring information, supplemented by data from the supporting tests listed in Table 8.3.2.2-7 and laboratory core testing, will be used to determine the extent and characteristics of the damaged rock zone around underground openings due to excavation and (or) local overstressing. Data will also be used in the analysis of interactions between the rock mass, tunnel excavation, and ground support system. Information from rock support and deformation monitoring will then be used to support and validate constitutive models describing rock behavior for various locations of interest in the Exploratory Shaft Facility (Section 8.3.2.5). Through data gathering and analysis for the monitoring program, the post-excavation rock mass conditions and influencing parameters will be evaluated.

8.3.2.2.3.4.2 Mine-by test.

The mine-by test will gather information to evaluate the geomechanical and hydrological response of the basalt rock mass and the behavior of the ground support system during excavation of a repository-sized drift. Drift excavation will simulate conditions projected for construction of an actual repository drift. The monitoring approach for obtaining deformation data is similar to the rock support and deformation monitoring program. Geologic characteristics in the rock mass (e.g., rock mass quality, fracture characteristics), and hydrologic regime (e.g., conductivity, pore pressure, inflow rates), stress redistribution, and mechanical properties will be documented. Additionally, geophysical parameters (e.g., electrical and acoustical properties) will be examined.

In contrast to the rock support and deformation monitoring program, data will be gathered during and after drift excavation. Therefore, elastic and inelastic behavior can be examined. Data collected will be used to confirm the validity and adequacy of constitutive models (Section 8.3.2.5) in predicting rock mass behavior, which, in turn, will support repository design and performance assessment. In this way, the mine-by test represents a practical means to demonstrate the constructibility of a prototypic repository opening and to identify deficiencies with the proposed construction and ground support methods. The mine-by test drift will provide an extensively characterized location for additional large-scale tests such as the room-scale heater test.

Prior to excavation, monitoring instruments will be installed peripherally to the unexcavated mine-by drift in boreholes drilled from one overhead and two lateral observation galleries. As the mine-by drift is excavated between the observation galleries, the peripheral instrumentation will be monitored electronically through a data acquisition system. As the test proceeds, tunnel convergence data and geologic, geophysics, hydrologic, and construction information will be obtained from the mine-by drift itself. Monitoring will continue after the excavation has been completed and until equilibrium has been established.

An important function of the mine-by test is to assess the physical changes and related mechanical damage of the tunnel wall rock since being in its preexcavation state. All available data will be examined to evaluate the effect of the tunnel excavation method and ground support system on the extent and severity of the damaged rock zone. Mechanical damage in the rock mass may also be promoted by local, anomalous stress concentrations, if present, which are less directly related to the excavation method.

8.3.2.2.3.4.3 Full-scale heater test.

The full-scale heater test is a simulation of a high-level nuclear waste package installed in a prototypic emplacement borehole. This test will be conducted in conjunction with a room-scale heater test (8.3.2.2.3.4.4) in the mine-by test drift. This location will provide a repository-scale drift that has been extensively characterized during the mine-by test. An electric heater will simulate the heat load expected from an actual waste container. The heater assembly will consist of a central heater, packing material, and a liner between the borehole wall and the packing material. Rock mass response around the heater will be determined by monitoring the temperatures, deformations, and stresses for the duration of the test. Additional information about the effects of heating will be obtained from geophysical measurements, borehole jacking, and borehole hydrologic testing. Stress measurements by overcoring and possibly hydrofracturing will also be performed in the rock surrounding the test both before and after heating. Geologic mapping and inspection of rock surfaces and boreholes, core logging, and laboratory testing of core samples will be done before and after operation of the heater test.

Thermomechanical response data for the full-scale heater test will be used to confirm numerical thermal and thermomechanical models. These models will, in turn, be used for design validation and in performance assessment applications. The test will provide direct evidence of the stability and characteristics of the horizontal emplacement borehole concept.

8.3.2.2.3.4.4 Room-scale heater test.

The primary purpose of conducting a room-scale heater test is to obtain measurements of the thermal and thermomechanical response of the basalt to waste emplacement on a larger scale than does the full-scale heater test. It accomplishes this by simulating a prototypic waste emplacement room and placing horizontal heaters at a given pitch down both sides of the room.

The room-scale heater test will be conducted in conjunction with the full-scale heater test. One heater will simulate a prototypic high-level waste package; the other heaters will simulate waste containers in heat load only (i.e., they will not be full size). Temperatures, deformations, and stress changes in the rock mass along the drift will be measured. Additional information about the effects of heating will be obtained from geophysical measurements, from which hydraulic conductivity can be calculated. Stress measurements by overcoring will also be conducted before, during, and possibly after the heating process. Geologic mapping, core logging, and laboratory testing of core samples will be done before and after heating the drift.

Data from the room-scale heater test will be used to confirm numerical thermal and thermomechanical models. These models will, in turn, be used for design validation and in performance assessment applications. The test will permit the evaluation of the effects of heat on opening stability and excavation support systems.

The room-scale heater test and the full-scale heater test will be conducted in the mine-by test drift where the rock will already be well characterized, thus providing a comprehensive evaluation of excavation and thermal loading on the rock mass behavior.

8.3.2.2.4 Application of results

Results of the investigation of geomechanical properties of the host rock will be applied to the resolution of performance and design issues described in Section 8.2. Specific application of the parameters included in the investigation is shown in the tabulated parameter lists (Tables 8.3.2.2-2 and 8.3.2.2-3) contained in Section 8.3.2.2.2. The table contains a listing of the analytical tools (Section 8.3.2.5) used to determine certain performance measures relating to specific issues. Geomechanics parameters required for each of the analytical tools are listed in the table.

Following is a brief description of the aspects of repository design requiring information gathered in the investigation for each repository subsystem (shafts, underground openings, ventilation requirements, backfill requirements, muck-handling systems, and repository seals) in which the information is used. The discussions included cover the anticipated host rock environment from preexcavation through post-waste-emplacement.

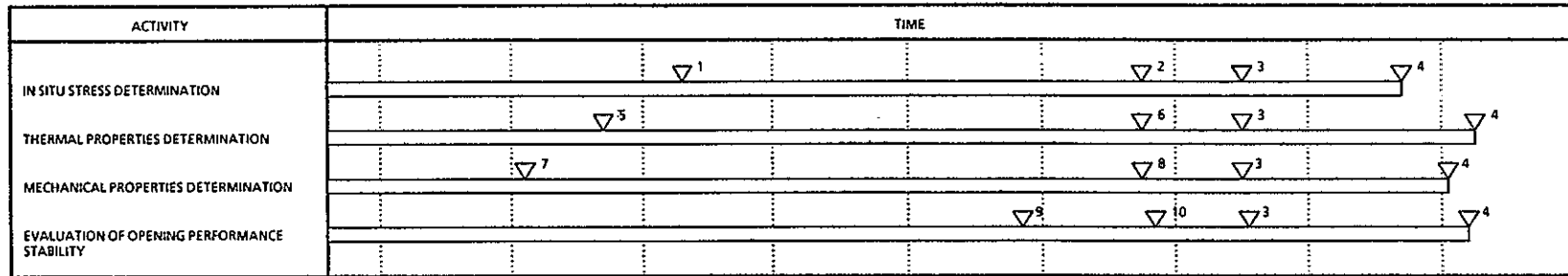
- Repository horizon--Selection of potential repository horizons within the host flow (i.e., floor elevation) is dependent on knowledge of the natural conditions of the host rock under investigation. One aspect of this selection will be an evaluation of the ease, cost, and practicality of siting, construction, operation, and closure of a repository. Several scoping analyses and parametric and tradeoff studies will be performed to determine the exact location of the repository horizon (see Chapter 6). The in situ stress state, mechanical and physical properties, joint characteristics and properties, and thermal/thermomechanical properties of the rock mass are required input.

- Shafts--The stress state (magnitudes and directions) in the rock mass, rock mass mechanical properties, mechanical properties of joints, and the thermal/thermomechanical properties of the host rock are parameters used in the design of repository shafts. These parameters are used to determine maximum shaft diameters, method of excavation, ground support requirements, and methods of casing, lining, and grouting of these shafts. Determination of methods and materials for shaft sealing at repository closure also relies on the use of these parameters.
- Underground openings--The design of underground drifts and other openings will depend on the geomechanical characteristics of the host rock. In situ stress, thermal properties, and mechanical properties of the rock and characteristics of joints in the rock mass are all input parameters to design analyses. Prototypic excavations, characterization of rock damage, and support system performance (under the opening performance study) will allow for direct verification and development of underground opening design. Design features include the extent of shaft pillars and openings such as shaft stations, access drifts, emplacement rooms, ventilation drifts, intersections, raises, and emplacement boreholes. Aspects of opening design affected by the host rock environment are layout, spacing, orientation, size, shape, support requirements, and method of excavation. Opening stability during repository construction and operation and decommissioning will be predicted by models developed in the repository geomechanics analyses investigation (Section 8.3.2.5) under the performance assessment program (Section 8.3.5).
- Ventilation requirements--Heat transfer from the host rock around emplacement rooms and access drifts to the ventilation air will directly influence the air flow requirements of the ventilation system. The thermal properties of the host rock are required as input parameters for thermal models that predict the heat flow from the rock to the ventilation air. Drift wall roughness will also influence air flow requirements of the ventilation system, and mechanical properties of the host rock coupled with the mining method employed will be required to make initial estimates of this roughness.
- Backfill requirements--Host rock mechanical properties and joint characteristics and properties will be used to determine backfill requirements for repository openings. Hardness and strength parameters are needed for design of the basalt aggregate manufacturing process for the backfill system.
- Muck handling systems--Mechanical and physical properties and joint characteristics and properties of the host rock (in conjunction with certain construction parameters such as hardness, abrasivity, cutability, and bulking factor) will be used to obtain preliminary estimates of maximum muck particle size.

- Repository seals--In the design of repository sealing systems, consideration must be given to the environmental conditions of the host rock in which the seals must function. The in situ stress state, mechanical and physical properties (intact rock and joints), and thermal properties of the host rock must be factored into the design and analysis of repository seals. These parameters are required to assess the effects of construction on sealing, the impacts of thermal loading, and the compatibility of the seals to the host rock environment, and to determine the hydraulic conductivity in the seal area. Seal performance prediction and design information also are required for the resolution of Issue 1.1 relating to the cumulative radionuclide release at the accessible environment.

8.3.2.2.5 Schedule and milestones

The schedule information provided for investigations in this program includes the sequencing, interrelationships, and relative durations of the studies in the investigation. The schedule for these four studies is shown in Figure 8.3.2.2-2.



PSM-2014-8.3.2-2

- ▽¹ BEGIN SURFACE TESTING FOR IN SITU STRESS
- ▽² BEGIN ESF TESTING FOR IN SITU STRESS.
- ▽³ PROVIDE ROCK MECHANICS DATA FOR DRAFT ENVIRONMENTAL IMPACT STATEMENT/PERFORMANCE ASSESSMENT ANALYSES
- ▽⁴ PROVIDE ROCK MECHANICS DATA FOR SITE DESCRIPTION AND LICENSE APPLICATION.
- ▽⁵ BEGIN LABORATORY THERMAL PROPERTIES TESTING.
- ▽⁶ BEGIN ESF THERMAL PROPERTIES TESTING.
- ▽⁷ BEGIN LABORATORY MECHANICAL PROPERTIES TESTING.
- ▽⁸ BEGIN ESF MECHANICAL PROPERTIES TESTING.
- ▽⁹ BEGIN MONITORING OF ESF CONSTRUCTION ROCK SUPPORT AND DEFORMATION.
- ▽¹⁰ BEGIN MINE-BY TEST/ROOM-SCALE HEATER TEST.

ESF = EXPLORATORY SHAFT FACILITY

Figure 8.3.2.2-2. Schedule for geomechanics studies to determine host rock environment.

This page intentionally left blank.

9 2 1 2 5 5 5 0 4 4 8

8.3.2.3 Specific program for coupled interaction tests

Repository design, construction, operation, and performance assessment require consideration of thermal, hydrological, geochemical, and mechanical effects. Although often evaluated independently of one another in conventional design analyses, these phenomena often interact with the occurrence of one phenomenon affecting the behavior of another. Consequently, there is a need to identify those design, performance assessment, and site characterization scenarios where coupled phenomena may be significant, and develop strategies for quantifying their effects.

For the repository program, coupled tests are defined as tests in which the effects of one or more variables that affect the behavior of the host rock are examined. For example, a block test in which pore water pressure, temperature, and joint geochemistry are monitored to examine their effects on the response of the block to applied mechanical loads is considered a coupled test. Coupled phenomena are not considered to be a subset of the specific data needs identified in the issues resolution strategy, but simply a part of the basic information required to fully understand processes which affect repository performance. Some variables, elevated temperature and mechanical loading for example, will be actively applied and controlled in the in situ tests planned for site characterization. Others, such as pore water pressure and geochemistry will not generally be controlled, but will be monitored for changes during the execution of a test. Both of these types of tests will be considered in the definition of coupled tests. No specific investigations or studies are planned that rely on coupled interaction tests. However, the results of coupled tests will supplement the information derived from the studies described in Section 8.3.2.2.

Initially, coupled processes may be easier to study in a laboratory environment, where the variables are easier to control and evaluate, than in situ. The BWIP plans to conduct scoping studies in the laboratory to identify potentially important coupled processes. Further laboratory studies may be indicated for specific coupled processes based on the results of the scoping studies.

The BWIP hopes to extrapolate the results of laboratory experiments to the rock mass to aid in the design of in situ tests. The validity of the extrapolation will be evaluated through comparisons of lab data with large scale test results.

Table 8.3.2.3-1 lists tests planned during site characterization that may involve coupled effects. Details of the tests are not provided in this section, but can be found in the referenced SCP sections and study plans. Classification of the listed tests is somewhat subjective; however, Table 8.3.2.3-1 attempts to list the tests that are used to develop an understanding of one or more processes that may be affected by secondary processes active in the test environment. Additional tests to investigate specific coupled phenomena in detail may be required for processes that are demonstrated to be very significant by the tests indicated in Table 8.3.2.3-1. These tests will be identified in study plan updates as their need is

Table 8.3.2.3-1. Site characterization tests involving coupled interactions

Test or activity	Primary effects considered	Coupled phenomena considered	Site Characterization Plan/study plan reference
Laboratory thermal expansion test (dilatometer)	T, M	T, M	8.3.2.2.3.2/Thermal properties
In situ expansion test	T, M	T, M	8.3.2.2.3.2/Thermal properties
Thermal conductivity probe	T	H	8.3.2.2.3.2/Thermal properties
In situ block test	M	H, C	8.3.2.2.3.3/Mechanical properties
Triaxial shear	M	H, C	8.3.2.2.3.3/Mechanical properties
Direct shear	M	H, C	8.3.2.2.3.3/Mechanical properties
Bench-scale direct shear	M	H, C	8.3.2.2.3.3/Mechanical properties
Block shear test	M	H, C	8.3.2.2.3.3/Mechanical properties
Laboratory creep test	M	T, H, C	8.3.2.2.3.3/Mechanical properties
Mine-by test	M	H, C	8.3.2.2.3.4/Opening performance
Full-scale heater test	T	H, M, C	8.3.2.2.3.4/Opening performance
Room-scale heater test	T, M	H, C	8.3.2.2.3.4/Opening performance
Heated block test	T, M	H, C	8.3.2.2.3.4/Opening performance
Damaged rock zone characterization	M	T, H, C	8.3.2.2.3.4/Opening performance
Borehole geophysics tests	M	H	8.3.1.2.3.3.5/Physical rock properties

C = Chemical.

H = Hydrological.

M = Mechanical.

T = Thermal.

PST87-2005-8.3.2-19

identified; identification of any such tests is not possible at the present time given the limited information available regarding coupled phenomena. The tests listed in Table 8.3.2.3-1 are directly related to the site characterization information necessary for design and assessment of the repository subsystem. Coupled tests to address phenomena (particularly hydro/chemical and thermo/chemical) primarily pertinent to waste package and repository seals design are discussed in Sections 8.3.3.3 and 8.3.4.3, respectively. These phenomena include interactions between the rock and manufactured components such as repository seals, borehole liners, packing materials, and waste canisters.

Many of the processes involving multivariable phenomena are expected to be of secondary importance to determining the level of compliance with regulatory criteria. A complete assessment of the importance of the various processes cannot be made until actual data are available.

Repository design and performance analyses, discussed in Section 8.3.2.5, will incorporate those coupled processes determined to be significant from laboratory and field test results. Because of the variety of regulatory criteria addressed by the issues and the subsequent variety of analytical approaches used to resolve them, methods of incorporating coupled effects may differ from issue to issue. Analytical methods for considering coupled effects presently exist; however, data for specification of the methods are not available for the BWIP.

This page intentionally left blank.

9 2 1 2 5 5 5 0 4 5 2

8.3.2.4 Specific program for design optimization

In Section 8.3.2.4, repository design optimization is discussed from the need to fulfill regulatory design requirements through the issue resolution process to the optimum goal of deciding on the preferred design concepts that are obtained through studied choices of design alternatives. For a general discussion of regulatory requirements and issue resolution strategies related to design optimization, refer to Section 8.3.2.1. The discussions of the specific issue resolution strategies for issues linked to design optimization are found in Section 8.2.2. In Section 8.3.2.4, the relationship between design development, issue resolution, and site characterization is explained. The single best design concept will be achieved by conducting tradeoff studies in the advanced conceptual design. The tradeoff studies will evaluate alternatives on predetermined criteria such as performance, safety, cost, and schedule. The optimization of waste package and repository seals designs is addressed in Sections 8.3.4 and 8.3.3, respectively.

The present repository conceptual design, detailed in the SCP repository conceptual design report (KE/PB, 1987b) and summarized in Chapter 6, is one step in the overall repository design process. The SCP conceptual design report has identified additional information to be acquired during site characterization. According to the Mission Plan for the Civilian Radioactive Waste Management Program (DOE, 1985c), the SCP conceptual design will be followed sequentially by the advanced conceptual design, license application design, and the final procurement and construction design.

The advanced conceptual design is a continuation of the design optimization and design concepts development. In the advanced conceptual design, design alternatives are expected to be explored and design concepts and criteria refined for use in the license application design.

The current repository design is discussed in Section 6.2.1, and an overview of the overall design concept is presented in Section 6.2.2. The method of operation of the repository for the receipt, transport, emplacement, and retrieval of waste is described in Section 6.2.3; and the design of each of the major components of the repository is summarized in Sections 6.2.4 (surface facilities); 6.2.5 (shafts); and 6.2.6 (underground design). The backfilling option for the repository after completion of the required retrieval period is discussed in Section 6.2.7 and, finally, the design of the seals to be placed in the shafts and boreholes as part of closure and decommissioning is presented in Section 6.2.8. The waste package design is discussed in Section 7.3.

Background

The current SCP conceptual design evolved through three major studies: the preconceptual design beginning in 1977; the conceptual design beginning in 1979; and a number of supporting engineering studies beginning in 1983. The early conceptual design work was summarized in the Conceptual System Design Description (RKE/PB, 1983). Reports for the various engineering studies were published by Raymond Kaiser Engineers, Inc./Parsons Brinckerhoff Quade

& Douglas, Inc., in 1984 and 1985 and by Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc., in 1986 and 1987. Each stage of the repository design to date was guided by corresponding design criteria.

The design criteria are based largely on the following general considerations:

- Public health and safety.
- Worker health and safety.
- Pre-waste-emplacement groundwater travel time and direction.
- Postclosure containment and isolation.
- Security and operational safety.
- Capability to retrieve waste.
- Flexibility in design to deal with potentially adverse conditions.
- Repository operability.
- Host rock characteristics.

Generic requirements, performance criteria, and constraints were developed for each of the principal repository components in the Generic Requirements for a Mined Geologic Disposal System (DOE, 1986b) based on analyses of what is needed to achieve the objective of safe nuclear waste disposal in an environmentally acceptable and economical manner.

The Issues Hierarchy for a Mined Geologic Disposal System (DOE, 1987c) identifies the same key issues as the Mission Plan and the two subordinate issue classifications: (1) performance issues and (2) design issues. These issues are based on the regulatory requirements from 10 CFR 20 (NRC, 1987b), 10 CFR 60 (NRC, 1987a), 10 CFR 960 (DOE, 1987b), and 40 CFR 191 (EPA, 1986).

The design issues derive performance requirements for the engineered facilities from the performance issues and derive other specific design requirements from 10 CFR 60 (NRC, 1987a). Considerations within these design issues include postclosure waste isolation, preclosure radiological and nonradiological health and safety, and technical feasibility and costs.

Table 8.3.2.1-1 in the overview section lists the site characterization information needs defined by the issue resolution strategies for repository design Issues 1.11, 2.7, and 4.2. These issues also define the performance parameters and their goals. The geomechanics performance parameters are shown in Table 8.3.2.2-1 in the host rock environment section (Section 8.3.2.2).

Design optimization is achieved through the use of design methodologies, plans, and reports as indicated in Figure 8.3.2.4-1 (Section 8.3.2.4). Subordinate to the Systems Engineering Management Plan for the Office of Geologic Repositories (DOE, 1986c), the System Design and Development Plan (Mildon, 1986) is supported by four supplemental documents, which include the Design Methodology document (KE/PB, 1987a), design study identification document, design study logics document, and the issue resolution strategy document as shown in Figure 8.3.2.4-2. Released as separate supporting documents, they are the tools used for design and development. In conjunction with the Design and Development Plan, the design requirements document, data

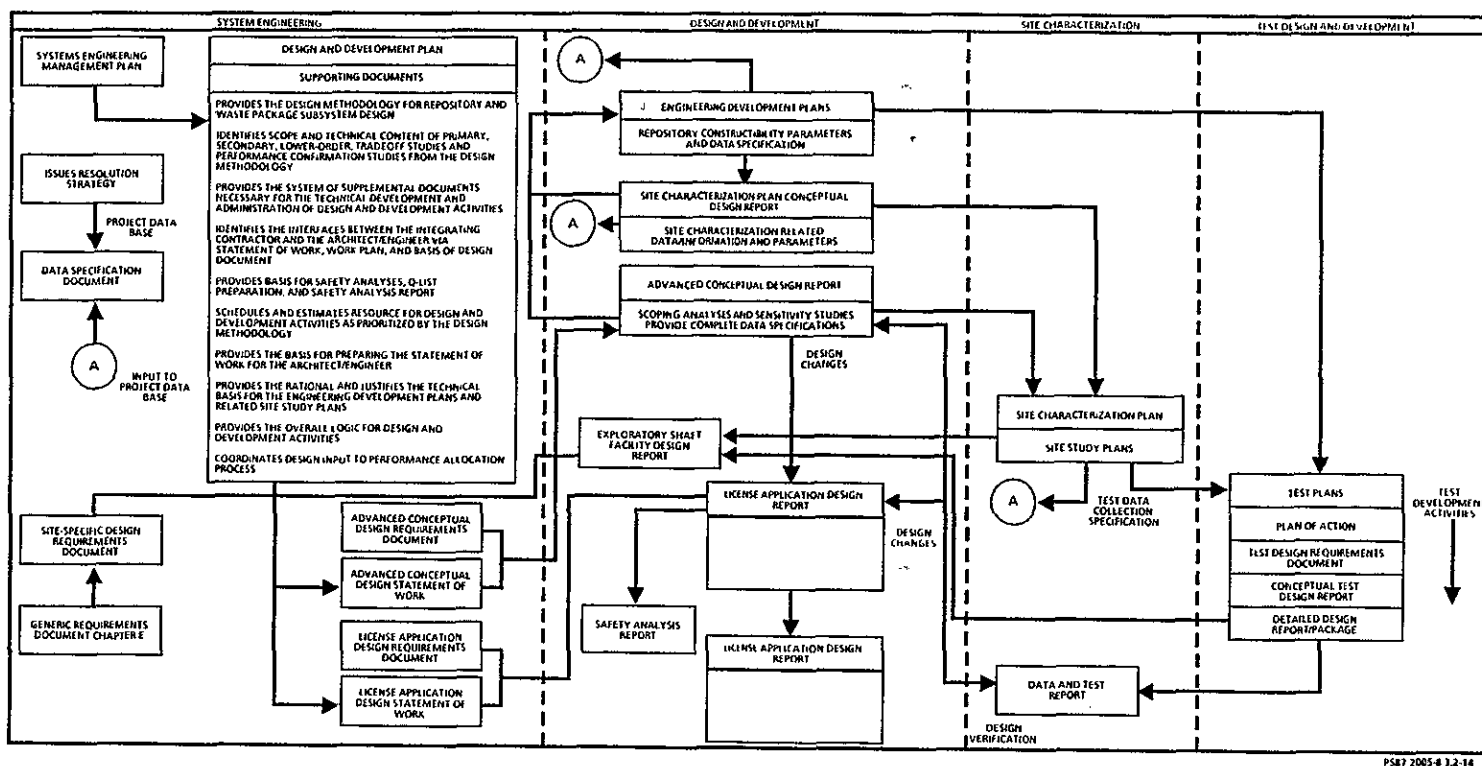
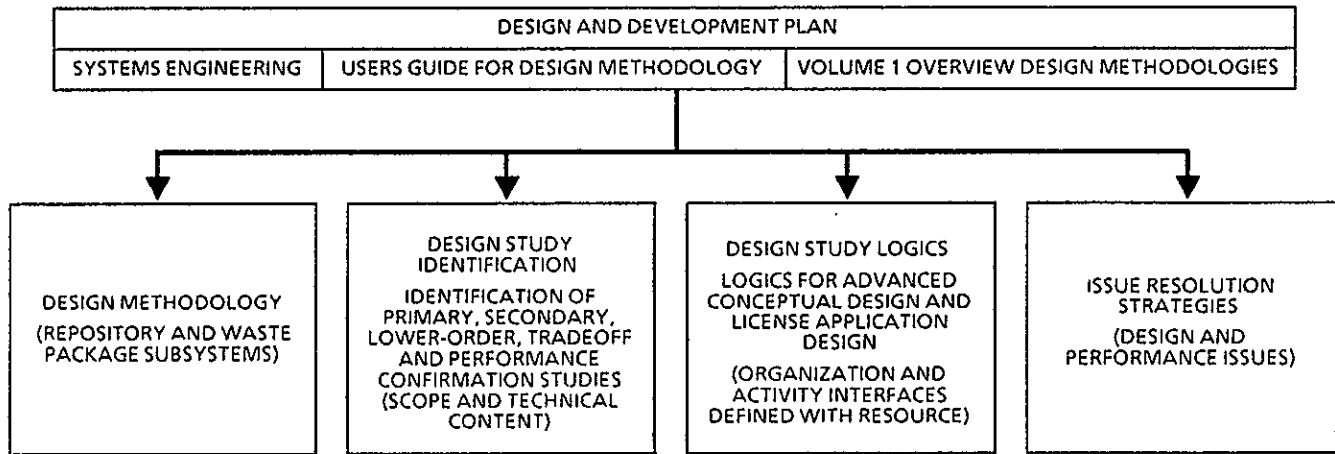


Figure 8.3.2.4-1. Technical documents used for design development and site characterization.

THIS PAGE INTENTIONALLY
LEFT BLANK



- DESIGN AND DEVELOPMENT PLAN (MILDON, 1986)
SYSTEMS ENGINEERING DOCUMENTATION
 - PROVIDES AN OVERVIEW OF THE DESIGN AND DEVELOPMENT PLAN AND THE PROCESS OF DESIGN AND DEVELOPMENT
 - IDENTIFIES THE DOCUMENT SYSTEMS USED FOR THE ADMINISTRATIVE AND TECHNICAL DEVELOPMENT OF DESIGN AND DEVELOPMENT ACTIVITIES
 - DESCRIBES THE SCOPE AND TECHNICAL CONTENT OF THE SUPPLEMENT DOCUMENT SYSTEM
- USER'S GUIDE AND VOLUME 1 OF THE DESIGN METHODOLOGY
- DESIGN METHODOLOGY DOCUMENT (KE/PB, 1987a)
 - 1.0 REPOSITORY
 - 1.1 SUBSURFACE
 - 1.2 WASTE HANDLING
 - 1.3 SURFACE
 - 2.0 WASTE PACKAGE
- DESIGN STUDY IDENTIFICATION DOCUMENT
STUDY IDENTIFICATION INCLUDING THE SCOPE AND TECHNICAL CONTENT OF THE PRIMARY, SECONDARY, LOWER-ORDER, TRADEOFF AND PERFORMANCE CONFIRMATION STUDIES BASED ON THE CURRENT REVISION OF THE DESIGN METHODOLOGY DOCUMENT
PRIORITIZATION AND RESOURCE IDENTIFICATION FOR THE STUDIES IDENTIFIED
- DESIGN STUDY LOGICS DOCUMENT
LEVELS 1 THROUGH 4 LOGICS
- ISSUE RESOLUTION STRATEGIES
COMPENDIUM OF INFORMATION AND PARAMETER NEEDS.

PS87-2005-8.3.2-13

Figure 3.3.2.4-2. Content of Design and Development Plan (Mildon, 1986) and supplemental documents.

specification document, and various statements of work, provide the framework from which the architect/engineer and other subcontractors can prepare a work plan and produce a series of design reports. The System Design and Development Plan (Mildon, 1986) provides an explanation of the design and development process as implemented through the use of the supplemental documents shown in Figure 8.3.2.4-3.

Key to the process of design and development is the strategy for design optimization presented in the Design Methodology document (KE/PB, 1987a). Information needs have been identified for siting studies, facilities design, and performance assessment to resolve design and performance issues, ensure that regulatory criteria are met, and support license application.

Engineering development plans and site study plans are used to plan and organize tests, studies, and associated analyses as shown in Figure 8.3.2.4-1. Data specifications produced from scoping or sensitivity analyses can be traced to repository design, construction, or site characterization related parameters as identified in the design and performance issues. These parameters are organized by engineering or scientific discipline into study plans.

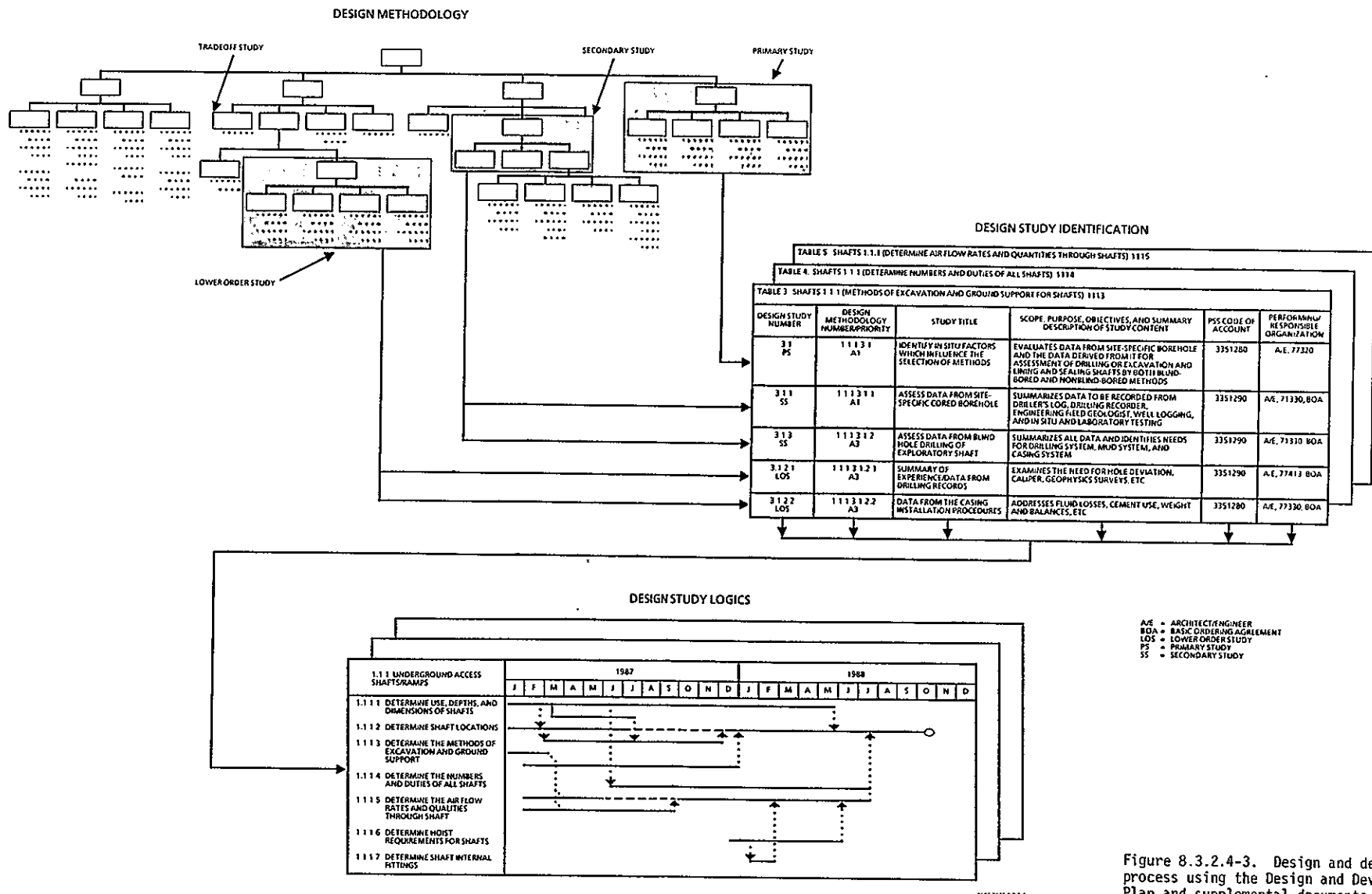
Engineering development plans are used to address information needs not related to site characterization and to encompass prototypic testing to provide construction and operations data and information in support of repository and waste package design and development. Examples of specific topics include retrievability, waste container fabrication, and waste handling and robotics. Engineering development plans are released as separate supporting documents.

Site study plans support site characterization and contain the descriptions of test activities, which are organized by scientific or technical content to include the disciplines of geology, geomechanics, hydrology and geochemistry.

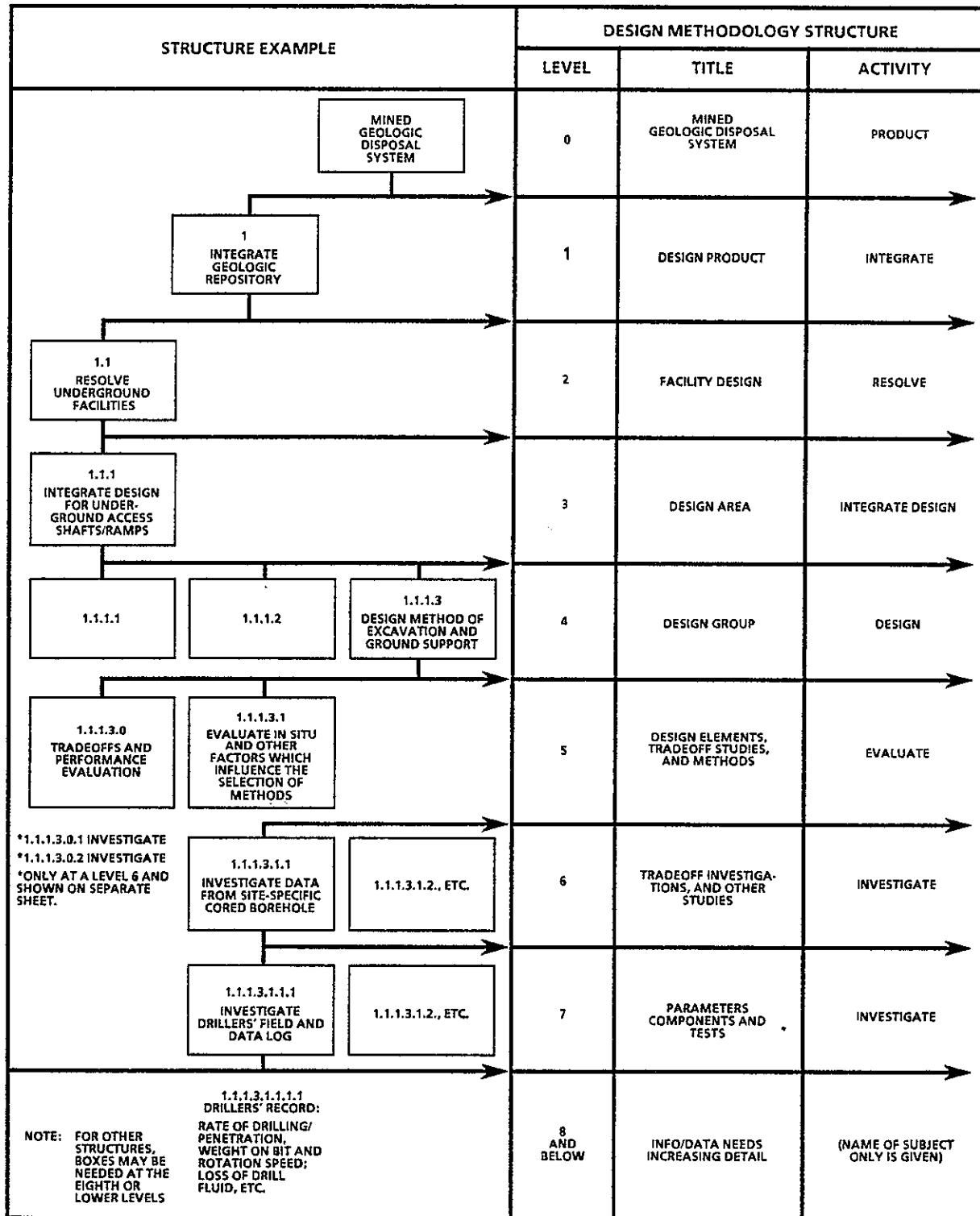
Test plans, which are a subset of study plans, are used to implement specific laboratory or in situ tests as part of the overall testing program. As indicated in Figure 8.3.2.4-1, the test data flow back to the primary design activity (the source of the data specification) for incorporation.

The design methodology provides a systematic reference base for the resolution of issues. In Figure 8.3.2.4-4, the different levels of the design methodology are illustrated. In Table 8.3.2.4-1, each level of the design methodology is defined and the controlling question presented that must be answered before the design proceeds to the next higher level and finally culminates in a repository design that resolves all the issues. Levels 5 and 6 in Table 8.3.2.4-1 are the levels at which tradeoffs or alternatives affecting design are evaluated.

To select the optimum design from several design alternatives, the design methodology has identified a number of tradeoff studies that are used to determine the best system design solutions to meet functional requirements.



**THIS PAGE INTENTIONALLY
LEFT BLANK**



PS87-2005-8.3.2-5

Figure 8.3.2.4-4. Design methodology structure and titles.

Table 8.3.2.4-1. Design methodology definitions and structure correlated to issues-related controlling questions

Design methodology level	Level title	Activity	Meaning	Question controlling development of level below
0	Mined Geologic Disposal System (MGDS)	Product	The highest level of the structure identifies the required product and its function	What are the products that must be developed at Level 1, if the MGDS is to resolve all performance issues as related to both waste isolation and operation/facility support?
1	Design Products	Integrate	A design product results from the integration of appropriate facility designs that produce affirmative answers to design issue questions and thereby resolve attendant performance issues. At this level there are the following two products: 1. Geologic repository 2. Waste package (Only the first of these has been developed at this stage.)	From which Level 2 facilities can these two products be integrated and provide resolution of the performance issues?
2	Facility Design	Resolve	A facility design resolves attendant performance issues resulting from the combination of design areas. Three geologic repository facility designs are identified as follows: 1.1 Underground facilities 1.2 Waste-Handling Facilities 1.3 Surface Facilities (1.3 and specific waste package design-methodology will be prepared later)	From which design areas can these facilities be combined to resolve performance issues?
3	Design Area	Integrate design	A design area develops an integrated design from associated design groups and derives its design goals, objectives, and criteria from the performance criteria.	What specific groups of designs can be integrated to develop each design area?
4	Design Group	Design	A design group develops the design of a single component, method, or group of components, which, when integrated with associated design groups, will constitute a design area.	What tradeoffs, components, and tests are needed to define design values and to support the analysis?
5,6	Design Elements, Tradeoff Studies, and Methods	Evaluate	At Level 5 the design elements, tradeoff studies, and methods that were investigated and analyzed at Level 6 are evaluated for development in a design group as a design activity.	What parameters, components, and tests are needed to define design values and to support the analysis?
6,7	Parameters, Components, and Tests	Investigate	Requirements, properties, parameters, or components that affect design loads, locations, dimensions, etc., are investigated.	What is required to provide input to investigations, analyses, and evaluations?
Below 7	Information/data needs	Name of subject	Groupings of individual information/data needs for characterization in descending greater levels of detail.	

PST87-2005-8.3.2-28

These tradeoff studies are conducted and evaluated with respect to performance, safety, cost, and schedule criteria requirements recognizing the constraints imposed by constructibility, operability, maintainability, and reliability on the system.

The characteristics of the geologic host rock and the surrounding hydrologic environment are important to engineering design. The SCP repository conceptual design report (KE/PB, 1987b) incorporates some assumptions in site characteristics that affect shafts, underground design and layout, operation, and closure for which data are currently lacking. Site characterization activities will provide the site data or information needs required. The existence and proximity of high-pressure aquifers above the host rock are considered to be extremely important in the repository design. Vertical connections from as yet undetected faults, shear zones, fissures, and unhealed joints could create conducting channels for potential inflows. Other site-related characteristics that affect the design are the magnitude of the in situ stresses and the presence of dissolved gases in the groundwater that will be liberated whenever quantities of water are encountered. The BWIP SCP conceptual design incorporates features that offer flexibility to cope with anomalies and zones in which adverse conditions may be found.

Summary of program

The mission of the basalt repository is to receive, emplace, and store spent fuel, high-level waste from the West Valley demonstration project, and defense high-level waste. The repository is also to maintain the capability to retrieve waste until it is determined that such capability is no longer needed. A conceptual repository design developed to fulfill these functions and meet the design requirements is described in Section 6.1.1. This conceptual design integrates the surface facilities, shafts, and underground facilities. These facilities are constructed in a sequence consistent with the proposed waste receipt schedule and in a configuration consistent with the conditions present at the proposed site.

Design is recognized as an iterative and developmental process with these predetermined specific outputs:

- Site Characterization Plan repository conceptual design report (KE/PB, 1987b).
- Advanced conceptual design.
- License application design.
- Final procurement and construction design.

In general, the underground facility design has the following similarities to a major mining project:

- Access to the underground facility must be obtained by constructing shafts, drifts, and (or) declines.
- The underground layout must use available space efficiently to permit use of the most effective excavation and ground support systems.
- Transportation systems must be provided.
- Ventilation must meet regulatory and operational requirements and provide a safe and acceptable working environment.
- Maintenance, supplies, utilities, and support services are needed.
- Potential water inflows must be anticipated and a means of dealing with routine and nonroutine inflows provided.
- At closure, entries from the surface to the mine must be backfilled and sealed.

For the above reasons, the ongoing design optimization will be based on proven and developing technologies and address alternative design approaches.

In addition to the normal underground and surface construction design constraints, this project has several unique factors that have never been previously addressed on any project. These factors are associated with the containment and isolation of radioactive waste material. Therefore, engineering decisions must be addressed for both the normal mining and construction considerations plus the following general list of special considerations:

- Radiation safety and criticality concerns.
- Transportation, storage, decontamination, canister fabrication, hoisting, emplacement, and monitoring of waste material.
- Long-term caretaker operations and the need to maintain the option for complete retrievability of the waste.
- Protection of sources of groundwater.
- Postclosure containment and isolation of waste.

8.3.2.4.1 Purpose and objectives

The immediate purpose of design optimization is to describe those design issues that necessitate data acquisition during site characterization. Specific analysis techniques, which may use models as described in Section 8.3.2.5, are identified, developed, and used to select specific parameters (e.g., size, spacing, uses, numbers, areal and vertical extent, and the related logistics systems for alternative components). Significant factors that may affect the resolution of design issues are identified to establish the design analysis requirements. Development of the design concepts and analysis techniques to resolve design concerns requires consideration of the following:

- Relationship to and methods chosen to resolve the performance and design issues.
- Test methods available or potentially developed for improving the data base.
- Alternative approaches to manage variances between conceptual design report data base and data resulting from completed tests.
- Alternative approaches for flexibility of design to be adopted if the conditions encountered during construction are at variance with the updated data base in certain localized zones.

Design verification controls design optimization to ensure that the design adequately specifies both the facility and the equipment that will satisfy the design criteria. Design verification includes evaluation, design review, and performance verification.

Eventual confirmation of the adequate performance of the design, repository components, equipment, and operating methods will be based on qualification and performance testing. Qualification testing will demonstrate the adequacy of the component or method in satisfying performance criteria under conditions simulating the most adverse conditions expected. Section 8.3.2.7 presents a discussion of the systems important to the radiological health and safety of workers while Section 8.3.2.8 addresses nonradiological health and safety of workers. On a preclosure basis, performance assessment is required to demonstrate the adequacy of the repository design with respect to cost, ease of siting, safety, operation, closure, and decommissioning of the repository. Details of postclosure performance assessment are described in Section 8.3.5.

The rationale for and approach to design optimization are described in the following section. Section 8.3.2.4.5, Schedule and milestones, presents the activity flow and describes an integrated program that progressively advances from this SCP through the construction of the repository.

8.3.2.4.2 Rationale

Site factors that influence the selection of alternative methods of construction are identified in the design methodology. Particular emphasis is placed on those conditions and parameters that indicate or reveal the existence of potentially adverse conditions as they affect the design of shafts, drifts, and other openings, and as they impact closure and decommissioning.

8.3.2.4.2.1 Surface facilities

Surface facilities designs are performed by traditional design disciplines using techniques and information that are well-established. The most suitable types of facility construction will be selected to safely and cost effectively meet surface requirements for site access, repository operation, and eventual decommissioning.

By studied choices of design alternatives, an optimum surface repository layout arrangement will be developed. Studies leading to this goal will provide information and data as input to architectural building layouts, bulk-handling arrangements, and the design of roads, railroads, earth works, and storm drainage systems.

The repository surface facilities that have been identified are, to a limited extent, dependent on site conditions. In contrast, the effects of site conditions on the underground facility are significant and discussed in Section 8.3.2.2.

8.3.2.4.2.2 Underground facilities

The rationale for the underground facilities design is to collectively address the underground operational requirements, in situ conditions, construction requirements, and postclosure containment and isolation of radionuclides for the purpose of providing, at reasonable cost and within an acceptable schedule, an underground facility capable of meeting all regulatory and functional requirements. The design activities required to provide the underground subsystem have been established in the design methodology. The methodology provides a systematic approach toward identifying alternative methods of excavation for the purpose of providing a flexible approach in dealing with a range of potentially adverse conditions. The information and data needs associated with these basic alternative concepts and approaches to underground facilities design have been discussed and developed in the SCP repository conceptual design report (KE/PB, 1987b).

8.3.2.4.2.3 Design analyses

The selected design concepts for various components will be analyzed in all future design stages using methods appropriate for the specific design phase. The analysis methods will lead to identification of necessary tests and studies to develop the site-specific data base for the evaluation and subsequent selection of design alternatives. The process of test design

itself may well depend on the use of models to determine the test configuration, development of algorithms, and a number of other key activities to develop the test.

In addition to the data resulting from the tests and studies used in the design process, the analysis will use information based on observation and empirical judgment. Analysis methods for various repository components will be based on the regulatory requirements imposed on the design and physical requirements due to site conditions or other operational and constructibility constraints. These areas of analysis would include general categories of study such as the following:

- Safety.
- Constructibility.
- Industrial engineering.
- Human factor engineering.
- Cost/benefit and schedule.
- Postclosure performance.

Empirical analysis uses available data to estimate design parameters and to establish sensitivity to these parameters (e.g., water, temperature, joint frequency). Numerical analysis parallels empirical analysis and interacts with frequently used numerical techniques and modeling. It also establishes design sensitivity in terms of geometry and controlling parameters (e.g., opening shape, cross section, stress, pressure, and temperature) by system monitoring. Observational analysis is used to refine empirical and analytical analysis methods. It includes measurement of both physical parameters and dynamic effects. The results help establish design modification requirements and validate analytical tools.

Safety analysis examines the impact of significant parameters and effects on reliability to determine expected risk to the general public and repository personnel. Techniques include system modeling, fault tree analysis, estimates of potential failure, failure modes and effects analysis, the frequency, magnitude, location, and consequences of postulated events and probabilistic risk analysis.

Constructibility analysis assesses whether the construction process can efficiently produce the designed subsystem or component. The analysis is based on and includes operations analyses, resource availability, cost, and schedule. Constructibility also establishes the basis for comparison of alternative construction technologies and methods appropriate to site conditions, (through definition of normal, off-normal, and potentially adverse conditions by addressing necessary flexibility, options, and contingency measures) recognizing schedule constraints, availability of personnel material resources, and ease of maintenance and repair. Industrial engineering analyses examine the means of assessing what is needed in the repository design and for repository construction and operation.

Analysis of human engineering factors will address accident scenarios. The results of the analysis will be used to identify and correct potential operator error by relocation or readjustment of action-initiating devices, equipment configuration, operations, and components.

Cost, benefit, and schedule analyses depend on the results of other analyses. Evaluation of decisions and results as they affect cost and schedule against potential risk and benefit can create input to tradeoff studies. These types of analyses are important in assessing the cost, safety, and technical feasibility of repository subsystems and components.

An analysis of the postclosure performance of the engineered barriers and the repository seals is done to assess the design's ability to contain and isolate radionuclides. This analysis is done by integrating the design aspects of the repository seals plus the engineered barriers (underground facilities and waste package). Separate analyses of the waste package, underground facility, and repository seals will also be done. All requirements concerning protection of groundwater sources, dose rate limitations to the public, and containment and isolation of radionuclides must be met by any viable design.

If these analyses show the inability of a design to satisfactorily demonstrate compliance with the design criteria, one or more of the following actions will be required:

- Improve the site data base by additional testing.
- Modify or use alternative method of analysis.
- Identify alternative design approaches capable of demonstrating compliance.
- Revise the design criteria if possible.
- Report that the design criteria cannot be met.

Table 8.3.2.4-2 taken from Chapter 6 is a summary of design considerations by element and assesses the quality of the current data base to support the design analysis. Chapter 6 provides an explanation of the nomenclature, legend, and basis of the assessments indicated.

8.3.2.4.3 Description of activities

The following are major design alternatives and systems to be investigated and evaluated:

- Waste package design alternatives.
- Waste package underground location design alternatives.
- Waste package emplacement system design alternatives.

Table 8.3.2.4-2. Design analysis data requirements

Element by facility	Included in design?				Rock properties data					Other data
	Stability ^a	Groundwater control	Ventilation	Other	Geological ^b	Geomechanical ^c	Thermal ^d	Groundwater flow ^e	Rock mass strength ^f	
Underground facilities										
Preclosure										
Openings	Yes	Yes	Yes	NA	ID	ID	ID	ID	ID	NA
Shaft station	Yes	Yes	Yes	NA	ID	ID	ID	ID	ID	
Drifts	Yes	Yes	Yes	NA	ID	ID	ID	ID	ID	
Rooms	Yes	Yes	Yes	NA	ID	ID	ID	ID	ID	NA
Short horizontal borehole	Yes	No	No	NA	ID	ID	ID	ID	ID	
Layout	Yes	Yes	Yes	Operations	ID	ID	ID	ID	ID	
Postclosure										
Backfill	Yes	No	No	NA	ID	ID	SD	SD	ID	NA
Seals	Yes	Yes	No	NA	ID	ID	ID	ID	ID	
Surface facilities										
Flood control	Yes	Yes	No		SD	SD	SD	SD	SD	g
Civil	No	No	No	h	SD	SD	SD	SD	SD	g
Structural	Yes	No	Yes	i	SD	SD	SD	SD	SD	g
Shafts										
Preclosure	Yes	Yes	Yes	Operations	ID	ID	ID	ID	SD	NA
Postclosure										
Backfill	Yes	No	No		SD	ID	ID	SD	SD	NA
Seals	Yes	Yes	No	NA	ID	ID	ID	ID	SD	NA

^aIncludes seismic analysis^bSCP reference 6.3.2.5.1.^cSCP reference 6.3.2.5.2.^dSCP reference 6.3.2.5.3.^eSCP reference 6.3.2.5.4.^fSCP reference 6.3.4.^gTopographic map, climatology, geomorphology.^hRoad/drain.ⁱBuilding foundation.

ID = Insufficient data.

NA = Not applicable.

SD = Sufficient data.

PST87-2005-8.3.2-27

- Repository layout.
- Access shafts.

In Figure 8.3.2.4-5, the sequence in which the repository design alternatives must be accomplished is shown. All of the repository design is based on the waste package design, the waste location underground, and the emplacement system.

These alternative design activities, illustrated in Figures 8.3.2.4-6 through 8.3.2.4-9 and described in the following sections, are conducted and evaluated with respect to performance, safety, cost, and schedule requirements, recognizing the constraints imposed by constructibility, operability, maintainability, and reliability on the system.

8.3.2.4.3.1 Waste package design alternatives

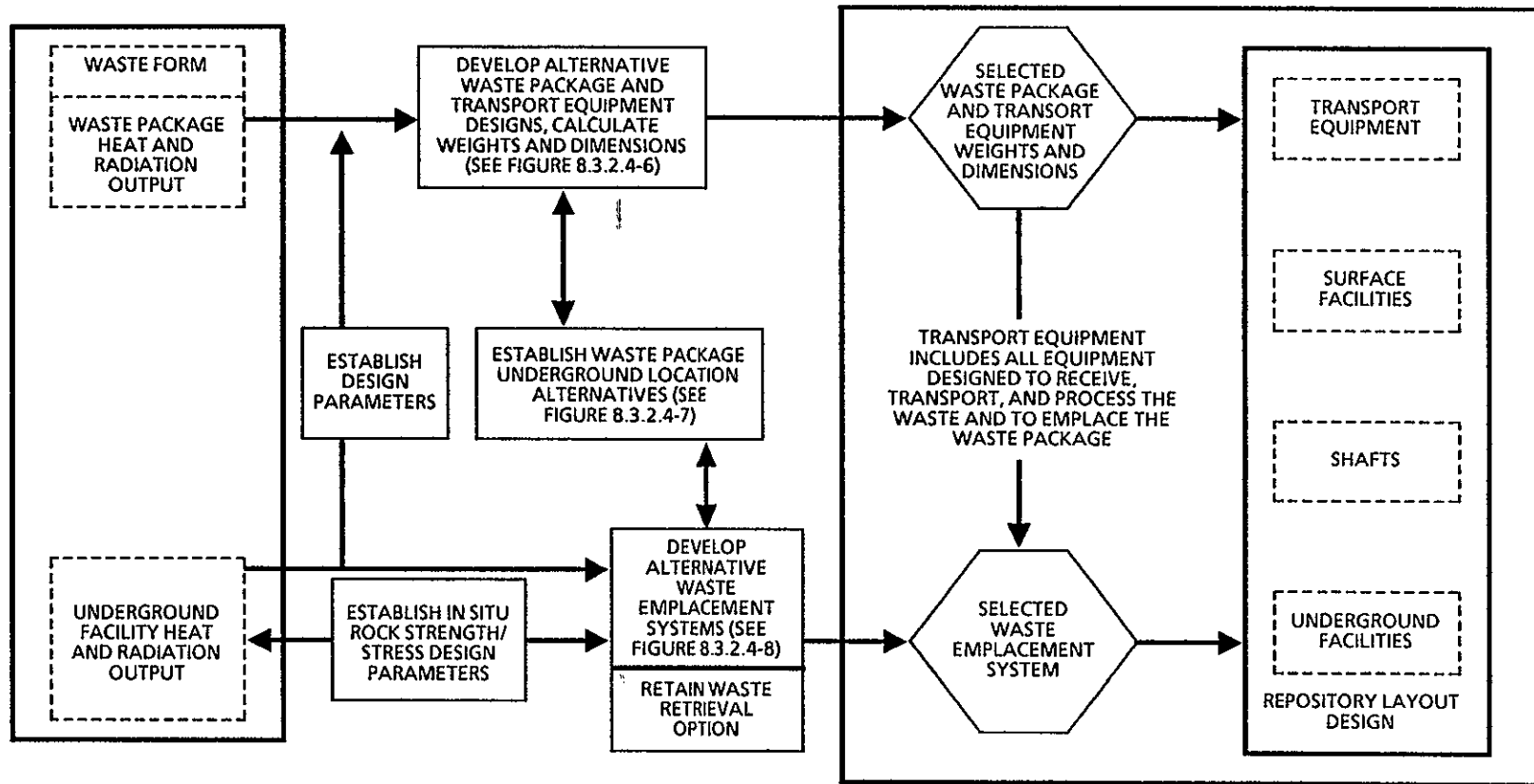
Ongoing development of alternative designs of the waste package (for improving safety during emplacement and for better long-term isolation) may result in proposals to increase or decrease the shielding characteristics of the container, and may require a different thickness and type of packing material. This could create a need for a transfer cask of considerably greater weight and diameter than those currently identified in the SCP repository conceptual design report (KE/PB, 1987b) data base. Such changes would affect hoisting requirements, available space in the waste-handling shaft, and emplacement room size, all of which are of considerable significance to the design of the underground facility.

The reference waste package design is discussed in Section 7.3.1, alternative designs are described in Section 7.3.2, and waste package design development is discussed in Section 8.3.4.4.

In Figure 8.3.2.4-6, waste package design alternatives, the interactions between the waste form and the waste package, the waste package and the transport equipment, and the waste package and the hoisting equipment are illustrated. An integral part of the development of alternative waste package designs is consideration of the waste package emplacement rate to assure that the projected/estimated annual waste receipts can be packaged for disposal.

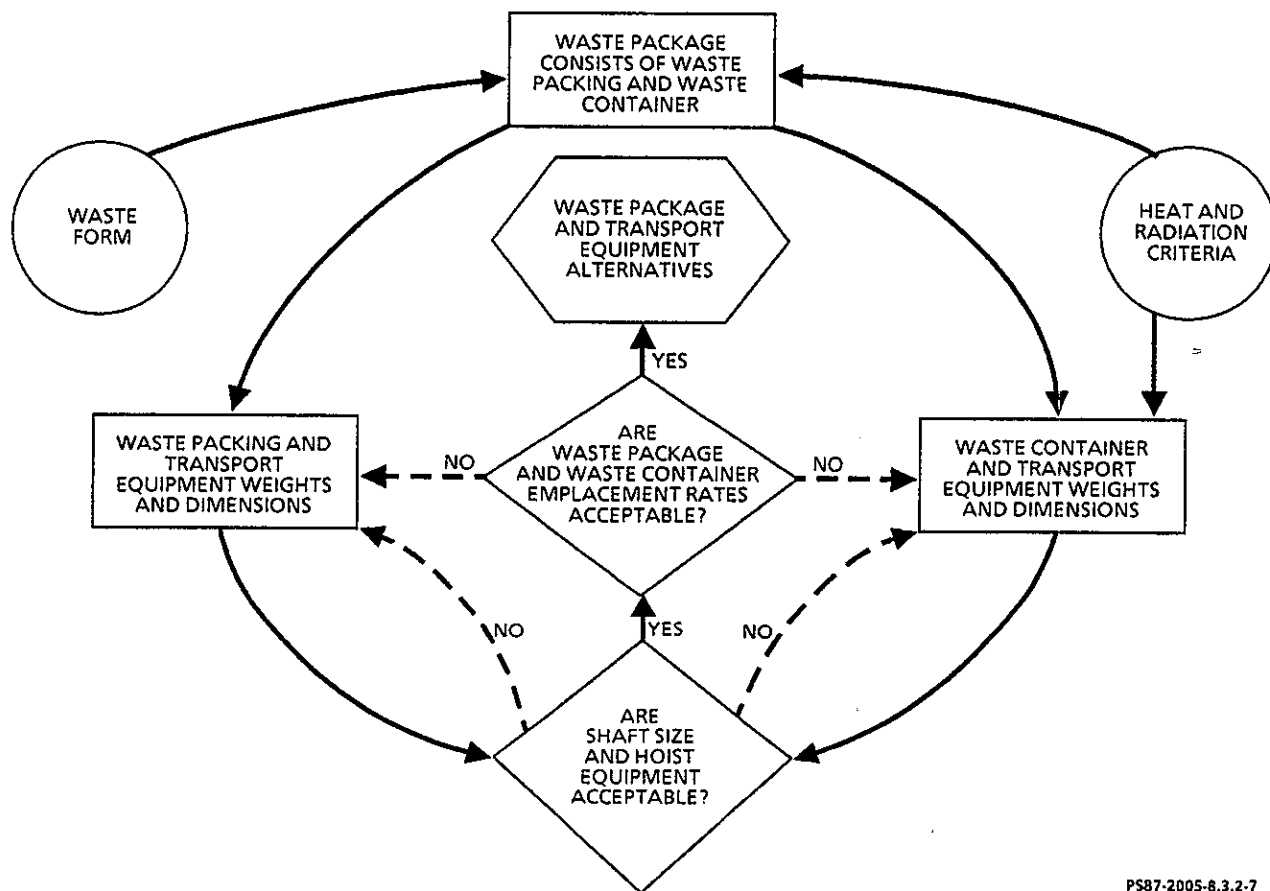
8.3.2.4.3.2 Waste package underground location design alternatives

Interactive with the waste package design is the design of the waste package emplacement location underground. The size, shape, heat, and radiation output of the package will be impacted by the emplacement location design and the design of the involved handling systems. The thermal output of the waste package is a determinate factor in sizing the repository. The packing design will also vary with the location design. In Figure 8.3.2.4-7, the interaction between the waste package and the underground emplacement location is shown.



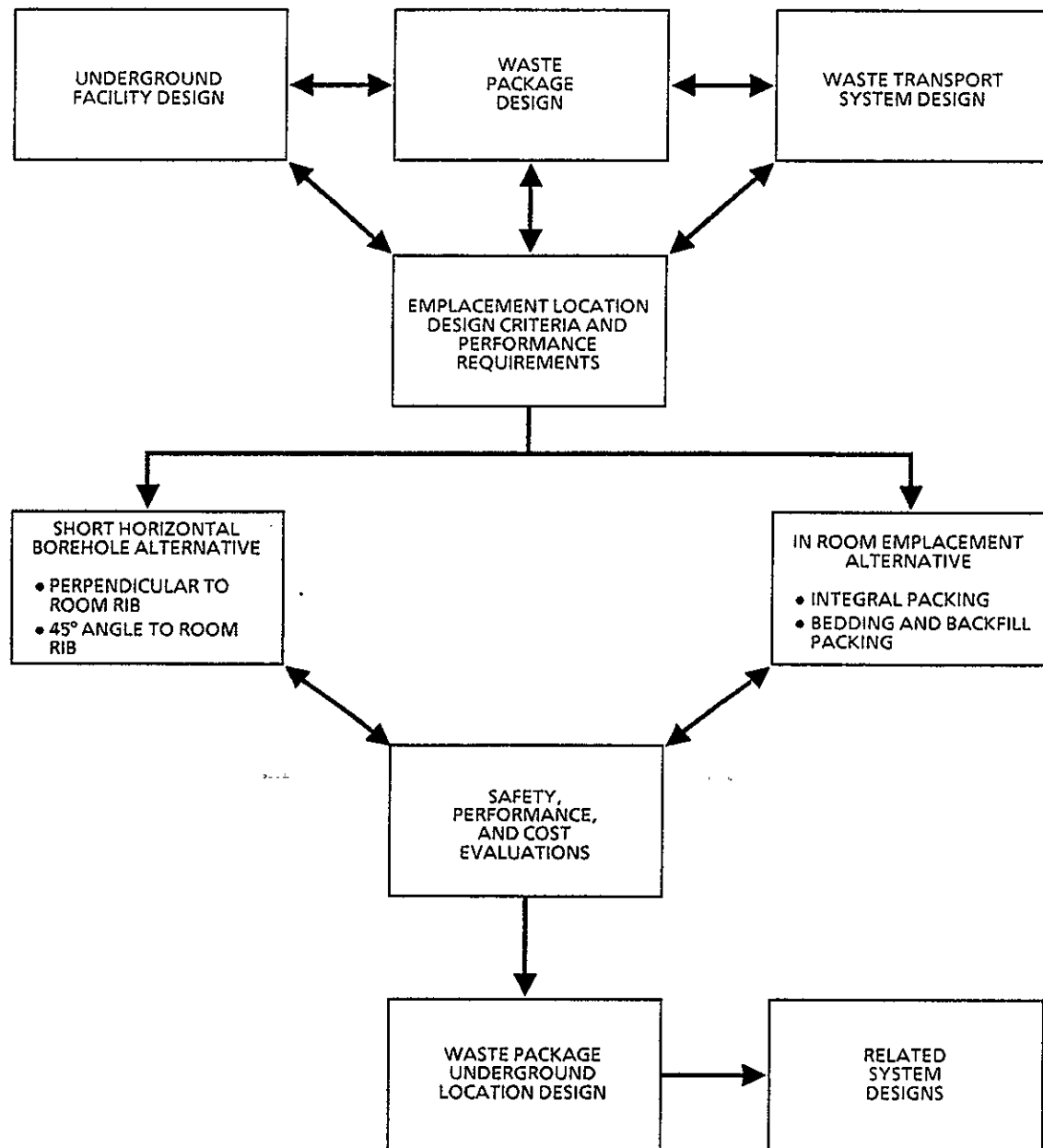
P587-2005-8.3.2.6

Figure 8.3.2.4-5. Repository design optimization sequence of design alternative activities.



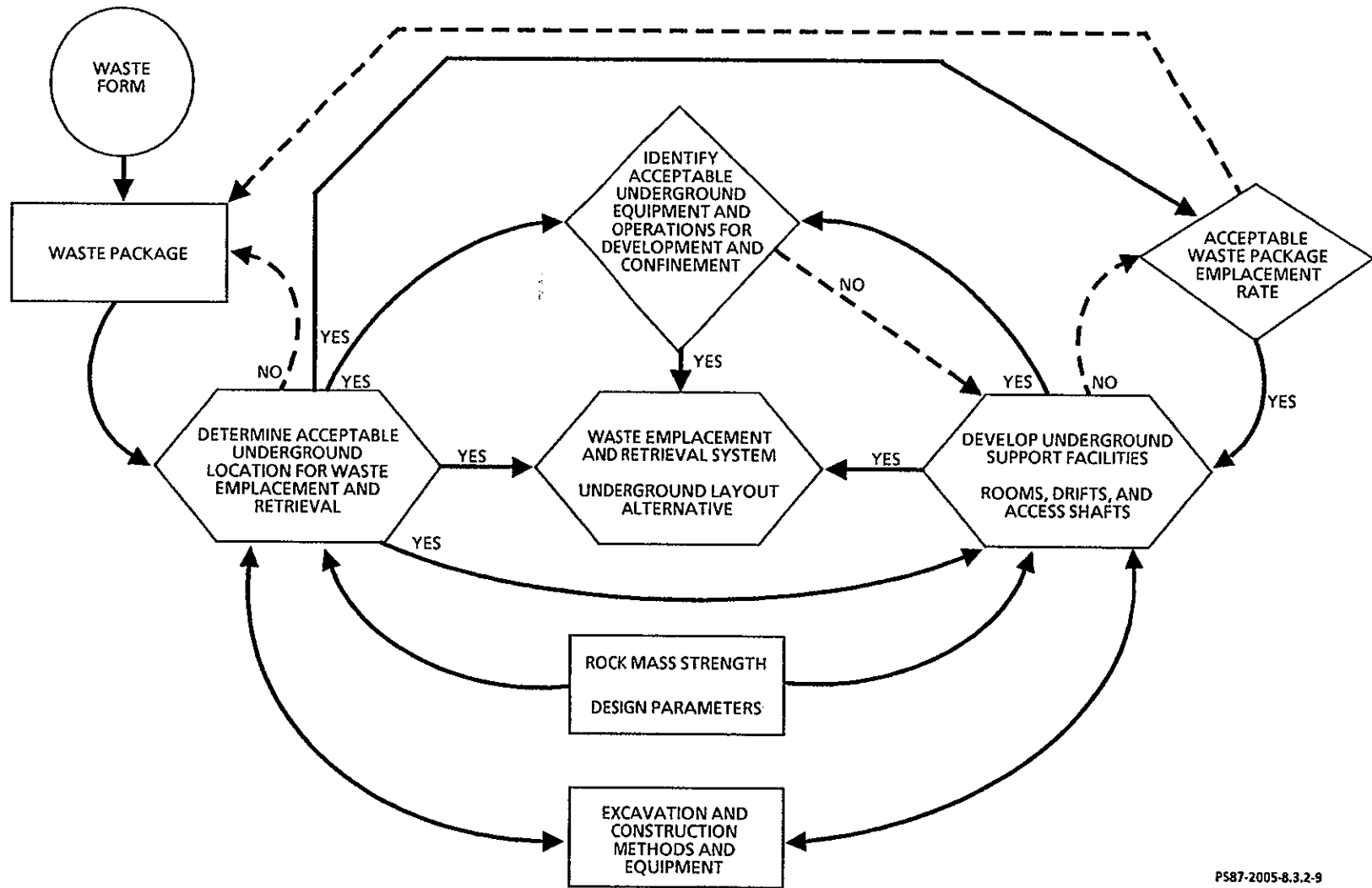
PS87-2005-8.3.2-7

Figure 8.3.2.4-6. Waste package design alternatives.



PS87-2005-8.3.2-8

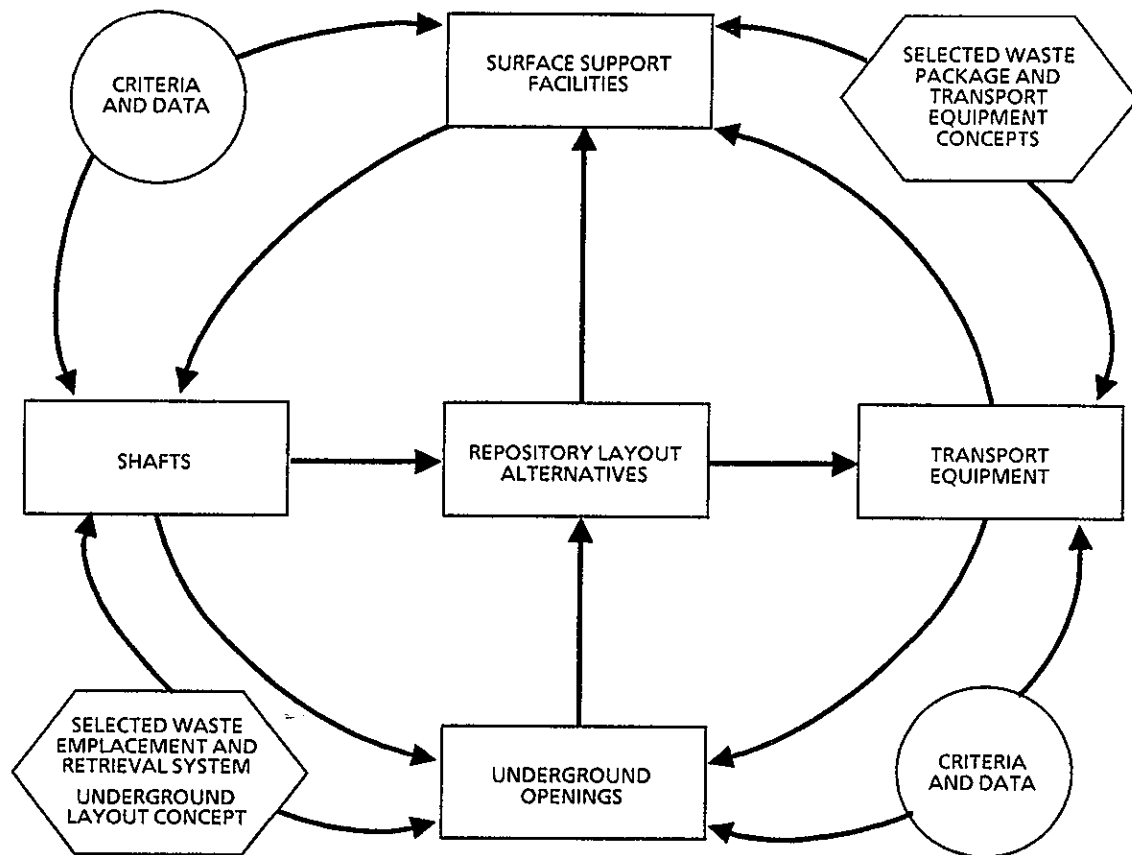
Figure 8.3.2.4-7. Waste package underground location design alternatives.



8.3.2.4-22

Figure 8.3.2.4-8. Waste emplacement system design alternatives.

PS87-2005-8.3.2-9



PS87-2005-8.3.2-10

Figure 8.3.2.4-9. Repository design dependencies impacting repository layout alternatives.

The present design concept (see Section 6.2.6.1.1) includes short horizontal boreholes oriented parallel to the direction of greatest horizontal stress and at right angles to the emplacement room. A viable design alternative to this concept would require that the borehole direction remains oriented parallel to the direction of greatest stress, but rotates the emplacement room axis to an orientation of 45° to the borehole.

A major alternative to the short horizontal borehole is the in-room emplacement with various packing options. These rooms would be oriented parallel to the direction of greatest stress and have a nearly round cross section. A major advantage of this design alternative is that it simplifies emplacement and retrieval. The postclosure containment could also be enhanced by the extensive use of packing-type material for bedding under the waste package and for partial drift backfill over the package.

Long horizontal boreholes and vertical emplacement concepts have been previously studied and discarded as less viable than the short borehole or in-room concept.

8.3.2.4.3.3 Waste package emplacement system design alternatives

In Figure 8.3.2.4-8, the interactions between the waste package and the waste emplacement hole, the waste emplacement and retrieval systems, the underground layout, and the underground support facilities are illustrated.

The following waste emplacement system alternatives will be evaluated and quantified through tradeoff studies with respect to safety, performance, and cost. Alternatives to be considered include the following:

- Remote automatic control of cask transporter travel and of handling functions with unmanned vehicle versus unmanned transporter unit.
- Manned transporter with a radiation shielding alternative based on allocating shielding requirement between the cask and the cab.
- Waste removal by means of the cask transporter versus a specially dedicated unit.
- Alignment alternatives for the positioning of the cask transporter.
- Power alternatives for all motive power systems (e.g., diesel versus storage battery power).
- Waste-transporter redundancy features (e.g., extra wheels).

8.3.2.4.3.4 Repository layout alternatives

The geologic repository is designed to be operable under conditions expected at the depth of the reference horizon and to satisfy specific requirements mandated by Federal regulations 30 CFR 57 (MSHA, 1985), 10 CFR 60 (NRC, 1987a).

Section 4.4 of the SCP repository conceptual design report (KE/PB, 1987b) describes design rationale and the current concepts for the underground layout and underground facilities; explains the relationship between the Exploratory Shaft Facility and the repository layout; and describes how the Exploratory Shaft Facility will be used during early development of repository operations. The layout description includes shaft stations, support facilities, utilities, access ways to emplacement areas, emplacement rooms and holes, and the water-handling system.

The repository is considered to be a system (of which the layout is an important component) and is designed to (1) provide radionuclide containment and isolation capability, (2) retain the natural isolation capability of the host rock, and (3) maintain the option to retrieve all waste during the preclosure periods. This implies that stability of the emplacement holes, emplacement rooms, and access drifts is a primary concern in the design.

The openings that comprise the underground layout are of different shapes and sizes depending on their function (access of personnel and materials, waste emplacement, air distribution, utilities, and other support activities). Appropriate excavation and ground-support methods are required to ensure safe conditions and long-term stability of the entire facility. The design approach for the underground subsystem layout is based on the following criteria:

- The orientation and geometry of the facility within the selected geologic horizon will be designed so as to contribute to the containment and isolation of radionuclides.
- The design will have sufficient flexibility to allow adjustments, where necessary, to accommodate specific site conditions and changes as identified through exploratory headings, probe-hole boring, in situ monitoring, testing, or excavation.
- The design will permit retrieval of nuclear waste in accordance with the performance objectives; openings will remain stable through permanent closure.
- Openings will be designed for safe operations and to reduce the potential for deleterious rock movement or fracturing of the overlying or surrounding rock.

- Layout design will meet the performance objectives for the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater pattern; physical characteristics of both the nuclear waste and the host rock will be determined from the extension of the emplacement area.
- Openings will be located beyond a set standoff distance from any known preferential pathway or unfavorable area.
- The rock support system will be designed so that the underground facility can be operated safely during the placement of waste plus during the caretaker period. The rock support system will also be designed so that preferential pathways are not created during postclosure. This may necessitate using structural backfill in critical areas.

The underground facility subsystem consists of a series of openings specifically designed and arranged to accommodate all subsurface activities associated with the safe and efficient operation of the repository. The underground layout represents the groupings of all these openings into an orderly and functional configuration that is comprised of components identified as pillar areas, access corridors, and emplacement areas, which are consistently laid out in modular form. A panel is an independent emplacement unit consisting of several rooms connected by short openings. Within these rooms are the openings or location where waste is emplaced.

In Figure 8.3.2.4-9, the interaction of the waste package and transport concepts, waste emplacement and retrieval system concepts, and underground layout concepts to create a repository layout is shown.

8.3.2.4.3.5 Access shafts design alternatives

The blind-drilling method of shaft construction was selected for the repository conceptual design (see SCP repository conceptual design report (KE/PB, 1987b)) because it has the least sensitivity to site characteristics including major water inflows. The shaft verticality required for a friction-hoist system for waste package lowering is a major constructibility concern.

The alternative shaft construction method under consideration is conventional (drill-and-blast) shaft sinking using freezing or grouting techniques. High temperatures at depth, the presence of water-bearing interbeds containing clays, the rate of strata water inflow, and the rate of fluctuation of hydraulic head are all matters of concern. Examinations already conducted indicate that an approach using ground freezing would be appropriate to deal with surface deposits, water, and other problem areas in the upper half of the shaft. The use of pregrouting or stage grouting during construction may be appropriate to deal with the hotter water-bearing zones during sinking of the lower half of the shaft.

If conventional shaft sinking is used for some of the shafts, then larger diameter shafts may be sunk, and the total number of shafts (presently required for ventilation) may be reduced. Blind-drilled shafts may be constructed much sooner than conventional shafts, but they are also more expensive. The involved alternatives must be carefully evaluated for safety, cost and schedule considerations. The constructibility information obtained from the exploratory shaft construction will provide a solid basis for this alternative evaluation.

8.3.2.4.4 Application of results

The advanced conceptual design will be used to select from design alternatives the safest, most cost-effective methods of repository construction that provide adequate postclosure performance.

The site characterization program will identify data or parameters that the repository design is sensitive to. These sensitivity analyses will provide guidance in the specification of testing program requirements.

Table 8.3.2.4-3 repeats Table 6.3-2 from Chapter 6 of the SCP and provides a preliminary assessment of the sensitivity of the design to site-characterization parameters identified in the current data base.

The sensitivity of design information (parameters and data) is important to the process of design development and affects the selection of design alternatives and performance of tradeoff studies. Information and data needs have been directly correlated by the Design Methodology document (KE/PB, 1987a) with specific repository subsystems, components, and the associated construction or operations activity for which it is needed. Beyond the initial assessment to identify significant parameter(s), it is important to recognize that it will be necessary to conduct sensitivity design analyses as a prerequisite to the development of the advanced conceptual design. Typically this will require bounding analyses and parametric and scoping studies, where appropriate. The tools required for these tasks will depend on the stage of development, phase of design, and sophistication of the models used in specific aspects of the design process. Details of the role, types of models, and methods of analyses are discussed in Section 8.3.2.5.

The parameters, components, and tests to be investigated during site characterization in support of the underground facility design are identified in the Design Methodology document (KE/PB, 1987a) at levels 6 and 7 under design methodology Section 1.1.2, as illustrated in Figure 8.3.2.4-10.

The subsystem components, parameters, and tests to be investigated during site characterization in support of shaft design are identified in the Design Methodology document (KE/PB, 1987a) at levels 6 and 7 under the integrated Section 1.1.1, underground access shafts and ramps.

Table 8.3.2.4-3. Site characterization data related to design and construction sensitivity

Facility factor (SCP section)	Sensitivity		Information needs	
	Design	Construction	Quality	Quantity
Underground facilities--openings--layout				
Geology (6.3.2.5.1)	Highly sensitive	Sensitive	SOA	Verify limits of data applicability
Geomechanics (6.3.2.5.2)	Sensitive	Highly sensitive	SOA	VDP
Thermal properties (6.3.2.5.3)	Sensitive	Moderately sensitive	SOA	VDP
Groundwater (6.3.2.5.4)	Sensitive	Sensitive	SOA	VDP
Strength of rock mass (6.3.4)	Very highly sensitive	Very highly sensitive	SOA	VDP
Surface facilities				
Topographic map (6.3.7)	Required as soon as possible, with special constraints identified	Sensitive	SOA	Required as soon as possible with special constraints identified
Climatology (near-term) (6.1.2.4)	Sensitive	Less sensitive	--	--
Climatology (long-term) (6.1.2.4)	Sensitive	Not applicable	SOA	VDP
Foundation (6.3.7)	Sensitive	Less sensitive	SOA	VDP
Shafts				
Geology (6.3.2.5.1)	Sensitive	Sensitive	SOA	VDP
Geomechanics (6.3.2.5.2)	Sensitive	Sensitive	SOA	VDP
Thermal properties (6.3.2.5.3)	Sensitive	Sensitive	SOA	VDP
Groundwater (6.3.2.5.4)	Sensitive	Highly sensitive	SOA	VDP

Source: After KE/PB (1987, Section 8.2.2).

NOTE: SOA = State of the art (available technology).
VDP = Verify design parameters.

PST88-2014-8.3.2-1

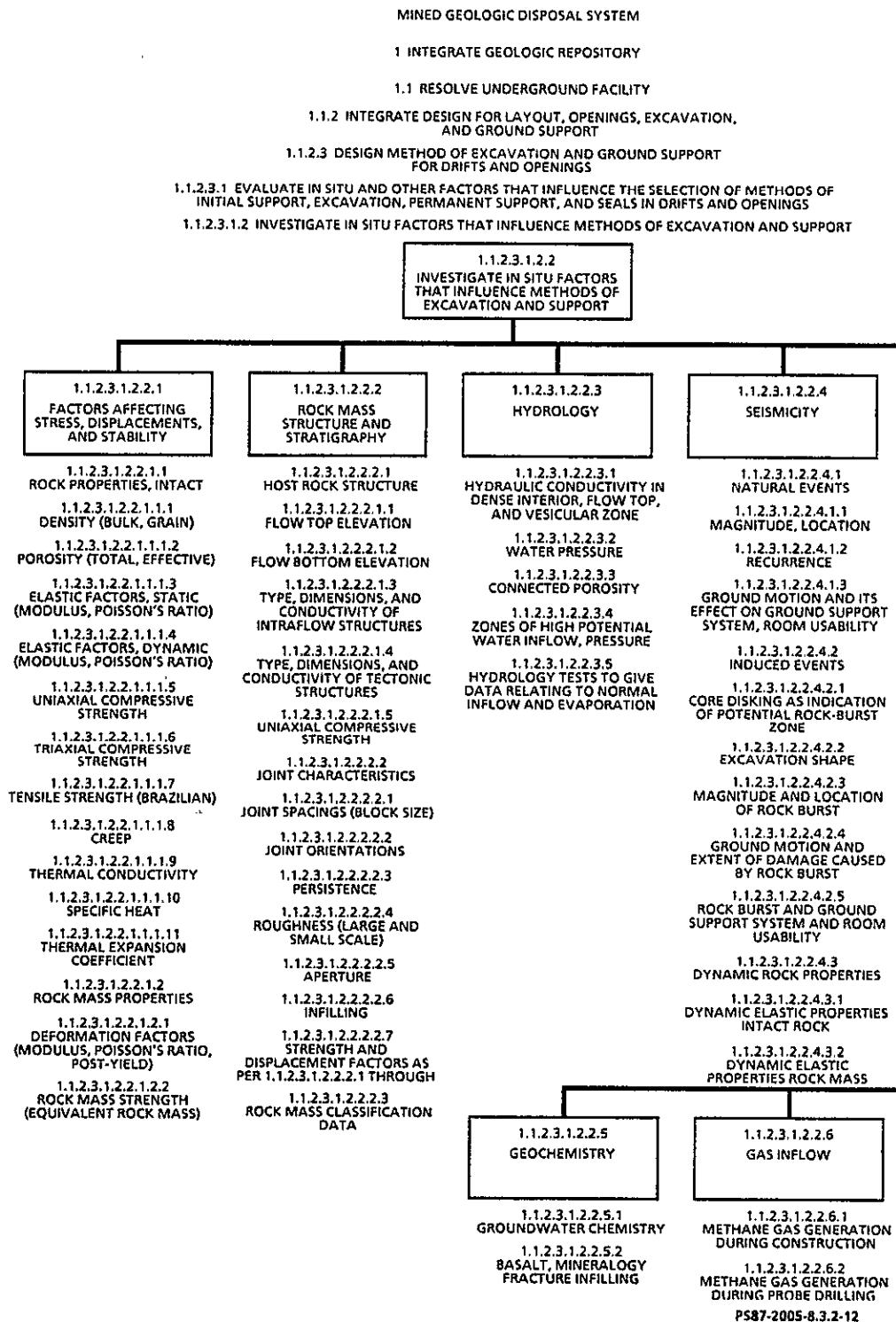


Figure 8.3.2.4-10. Example design methodology sheet.

8.3.2.4.5 Schedule and milestones

The design optimization activities leading to the design and construction of a repository are shown in Figure 8.3.2.4-11. The design development process identifies four major steps with predetermined specific outputs:

1. Site Characterization Plan repository conceptual design report (KE/PB, 1987b).
2. Advanced conceptual design.
3. License application design.
4. Final procurement and construction design.

The schedule for Step 2 and Step 3 is shown in Figure 8.3.2.4-12.

The first of the four major steps, the conceptual design phase, ends with the submittal of this SCP. The SCP repository conceptual design report (KE/PB, 1987b) supports this SCP and more particularly Chapter 6. It describes a site-specific conceptual repository design. The SCP conceptual design concentrates on surface facilities, underground systems, and waste handling.

The second and next major step is advanced conceptual design. Pre-ACD studies will explore design alternatives (Section 8.3.2.4.3) and refine design criteria. In the ACD preliminary drawings will be prepared, a construction schedule developed, and life-cycle costs estimated. Design-related licensing issues not defined in the SCP conceptual design report or resolved in the advanced conceptual design will be identified.

Between the advanced conceptual design phase and the license application design phase all previously identified and unresolved licensing issues will be resolved.

The license application design, the third step, shall demonstrate the resolution of design and licensing issues. Items necessary to demonstrate resolution of the issues hierarchy performance issues (DOE, 1987c) and the performance objectives of 10 CFR 60 (NRC, 1987a) (along with the license application requirements of 10 CFR 60.21) shall be submitted to NRC for review if the Hanford Site is selected.

For the site selected, final procurement and construction design, the fourth and final step, will be initiated. Nonlicensing-related ancillary systems will be designed during this step. Final design refinement for items necessary to demonstrate compliance with the design criteria and performance objectives of 10 CFR 60 (NRC, 1987a), development of construction bid packages for all systems, and development of final construction and procurement schedules will result in the production of contract documents for repository construction.

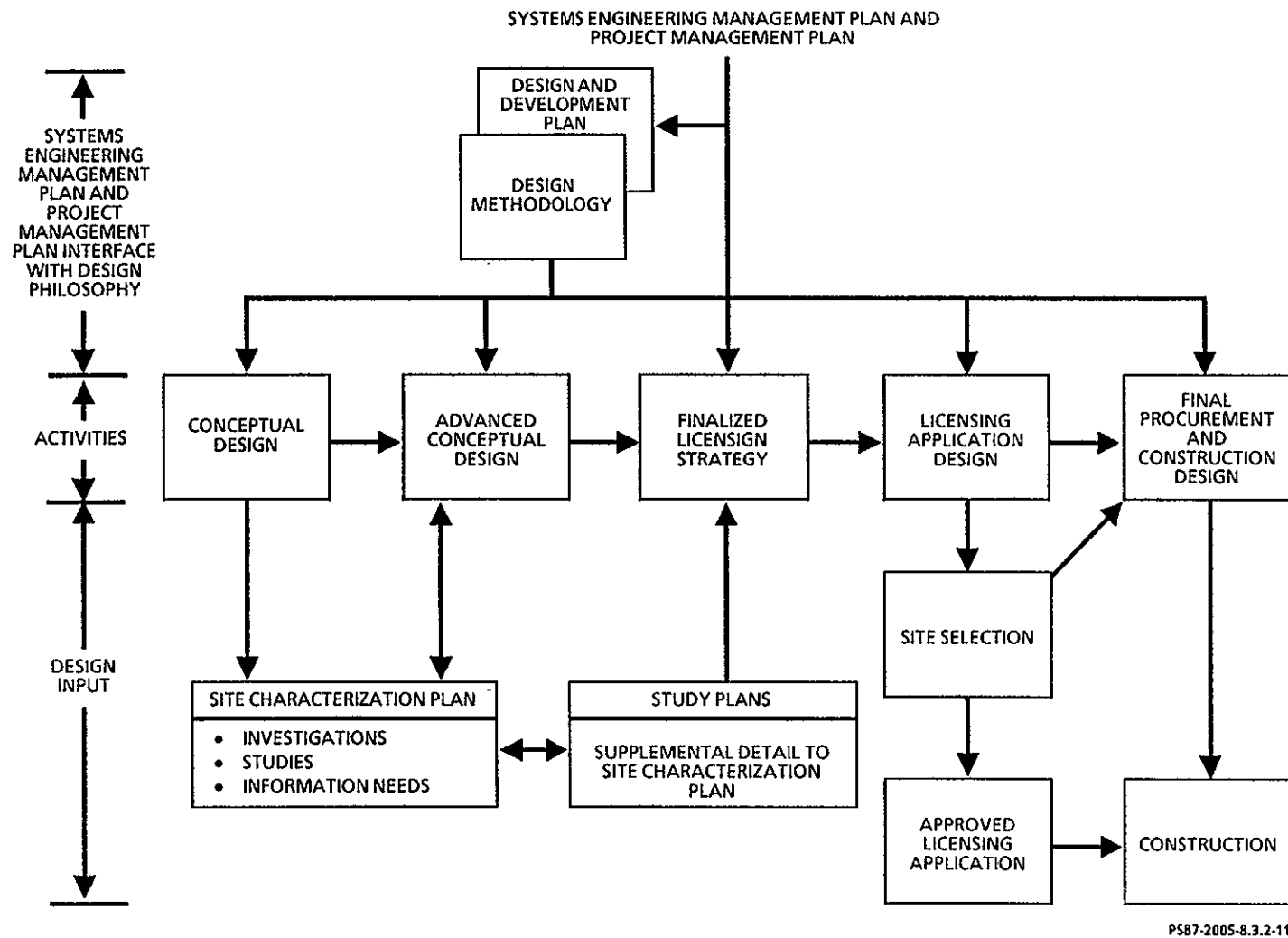
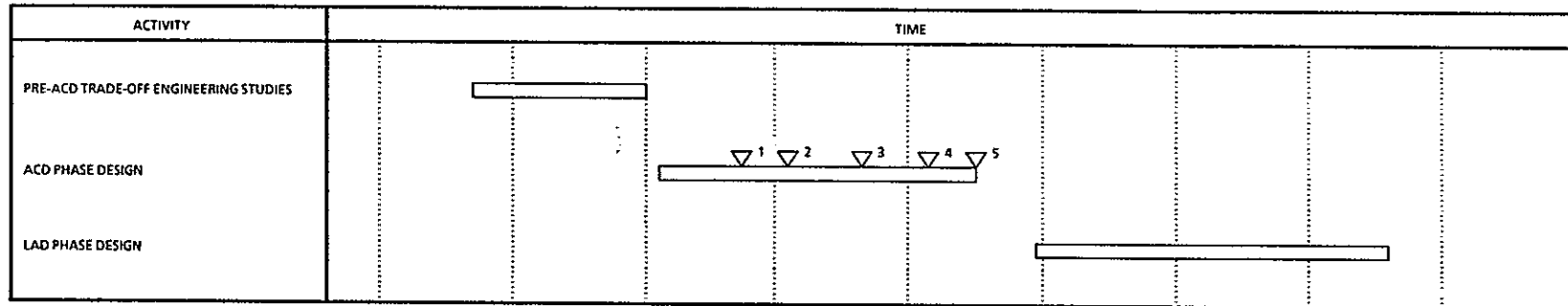


Figure 8.3.2.4-11. Activities leading to design and construction of a repository.



PSM 2014-8.3.2-3

THE PRE-ACD TRADE-OFF ENGINEERING STUDIES FOR DESIGN OPTIMIZATION ARE NOW IN PROGRESS; THEY WILL CONTINUE UNTIL THE START OF THE ACD. ANY REMAINING TRADE-OFF STUDIES REQUIRED TO FORM THE BASIS FOR THE ACD WILL BE DONE DURING THE EARLY PART OF THIS DESIGN PROCESS

- ▽ 1 COMPLETE DESIGN TRADE-OFF STUDIES.
- ▽ 2 30% COMPLETE.
- ▽ 3 60% COMPLETE.
- ▽ 4 90% COMPLETE.
- ▽ 5 ISSUED FOR APPROVAL COMPLETE.

ACD = ADVANCED CONCEPTUAL DESIGN
LAD = LICENSE APPLICATION DESIGN

Figure 8.3.2.4-12. Schedule for repository design activities.

8.3.2.5 Specific program for repository modeling

Development of the nuclear waste repository in basalt requires methods for analyzing design alternatives to allow selection and provide assurance of adequate performance of repository components. Development of the repository design as described in Section 8.3.2.4 will make use of models to evaluate the performance of repository components, thus allowing selection of appropriate alternatives. This section describes the investigations planned for repository model development and application activities that are to be conducted during the BWIP site characterization project phase.

The first of two modeling investigations, investigation of repository geomechanics models, identifies the models necessary to evaluate the repository opening stability during construction, operation, and decommissioning. In addition to the geomechanical modeling, other models are necessary to develop and support the repository design of the surface facilities, the shafts, and the underground facilities. These models are identified in the second "Investigation of additional repository design models." Additional models used for conducting safety analyses are covered in the following sections:

- Specific program for waste retrieval (Section 8.3.2.6).
- Radiological health and safety of workers (Section 8.3.2.7).
- Nonradiological health and safety of workers (Section 8.3.2.8).
- Strategy for preclosure performance assessment (Section 8.3.5.1).

Background

During site characterization, a geologic in situ testing program will be used to develop a site-specific geotechnical data base and to support use of analytical methods necessary for repository design and performance assessment. These analytical methods will be used in developing the basis for detailed data specifications for the site characteristics necessary to finalize the design and assess performance.

Various methods will be used to establish an acceptable repository design. One method used to support design analysis and selection of design alternatives based on safety and performance requirements is dependent on the ability to adequately simulate the repository system, subsystem, or component with a model. Identification, selection, and development of necessary models is based on the requirements placed on the design by established design criteria and regulatory criteria. These criteria include the needs to satisfy the issues on preserving the option of waste retrieval (Issue 2.4), on establishing compliance with the preclosure design criteria of 10 CFR 60.130 through 10 CFR 60.133 (NRC, 1987a) (Issue 2.7), on developing design and operating procedures to ensure nonradiological health and safety (Issue 4.2), on considering costs in selecting appropriate alternatives (Issue 4.5), and on satisfying the qualifying conditions of 10 CFR 960 (DOE, 1987b) on the preclosure system guideline and on the technical guidelines for surface characteristics, rock characteristics, hydrology, and tectonics.

The strategies for resolution of these issues presented in Section 8.2 have identified the following types of analyses requiring the use of models:

- Opening stability.
- Dynamic effects on stability.
- Airflow distribution.
- Air properties.
- Waste package integrity.
- Borehole integrity.
- Radionuclide transport.
- Radiation.
- Constructibility.
- Structural design analysis.
- Layout selection.

Design of a geologic repository is an iterative process that uses these and other types of analyses. Prior to the selection of the BWIP for site characterization, testing was conducted to develop an initial assessment of the geologic conditions and parameters characteristic of deep basalts. This testing involved geologic assessments from site-specific boreholes, hydrofracturing tests to estimate stresses, and laboratory testing of core samples. These data were used to develop the SCP repository conceptual design report (KE/PB, 1987b). Relatively simple geomechanics models were used to develop this design. Future design phases will use more complex geomechanical, ventilation, water inflow, facility design, and operations models to provide an adequate repository design that is responsive to the issues for a mined geologic disposal system. Additional in situ testing will be conducted during site characterization as identified in Sections 8.3.1, 8.3.2.2, and 8.3.2.3. As the geotechnical data base improves, more sophisticated analysis methods and models are to be developed to support advanced conceptual and license application designs.

Development of the repository design requires assessment of the risks and hazards, to which the general public and repository workers will be exposed, created by activities conducted at the repository during construction, operation, and decommissioning. Plans for evaluation of these risks are provided in Section 8.3.5.1, strategy for preclosure performance assessment. Plans for assessing the expected total system performance following permanent closure are presented in Section 8.3.5.2, strategy for postclosure performance assessment.

Summary of program

The specific program for repository modeling is comprised of two investigations. The first, investigation of repository geomechanics models, describes five geomechanic modeling activities for modeling the repository shafts, service openings, emplacement rooms, emplacement boreholes, and opening intersections. These models will be used to evaluate the stability of the proposed repository openings during construction, operation, and decommissioning. Material models associated with each of the geomechanics models will be developed in a study.

In the investigation of additional repository design models, two additional modeling activities are described. These cover the models necessary to conduct analyses in support of surface and subsurface facilities and equipment design. Required models include those for the design disciplines, operations, and system analysis, with special emphasis on underground ventilation, geohydrology (water and gas inflow), scheduling, and cost estimating.

8.3.2.5.1 Purpose and objectives

The purpose of the repository modeling activities is to provide a supportable basis for estimating the responses of repository components due to construction, operation, and closure of the proposed nuclear waste repository. Primary emphasis in the repository modeling activity is placed on the evaluation of the basaltic rock mass during the construction and operation phases. These models are necessary in the assessment of the retrieval option and opening stability requirements.

Additional modeling activities are required to allow identification and selection of reasonable cost alternatives, while maintaining the ability to satisfy the preclosure criteria. These models will be used in developing the plans for construction and operation, and for providing input to activities conducted for cost estimation.

Principal design objectives and elements for the repository that require use of models include:

- Waste emplacement configuration, including hole spacing, drift shapes, and other geometric parameters.
- Ground support selection and design.
- Overall repository layout.
- Definition of initial and continued monitoring requirements.

These objectives and principal elements are broad in scope and encompass many individual design elements. For example, design of underground openings requires specification of dimensions for waste emplacement drifts, waste emplacement holes, ventilation drifts, shafts, crosscuts, and intersections between openings. The proper design of each requires a prediction of the rock mass and support system behavior. Common practice is to make such predictions using empirical rules derived from previous experience and consideration of site- and project-specific parameters. These rules enable support systems to be specified without requiring detailed numerical analyses. In many situations, this practice has proved to be adequate even considering the difficulties in defining the characteristics of an underground site. However,

this approach may not be appropriate as the sole design approach for the nuclear waste repository in basalt because of the lack of previous experience in the rock type, temperature domain, and time scale being considered.

Requirements for the nuclear waste repository in basalt are in many ways unprecedented in both civil and mining engineering practice. This is due to the temperatures and thermal stresses that will be generated in the repository by the decaying waste, the length of time that systems (such as rock support systems) must perform adequately, and the need to ensure containment of radionuclides. The long-term performance in some cases cannot be completely verified by tests and measurements conducted in advance of construction.

Consequently, a more rigorous design approach is needed. Rock mass and support system performance during construction, operation, and decommissioning will be predicted by analytical methods with these predictions used for design purposes. Solutions for most of these analyses will be obtained by numerical approximations using computer codes.

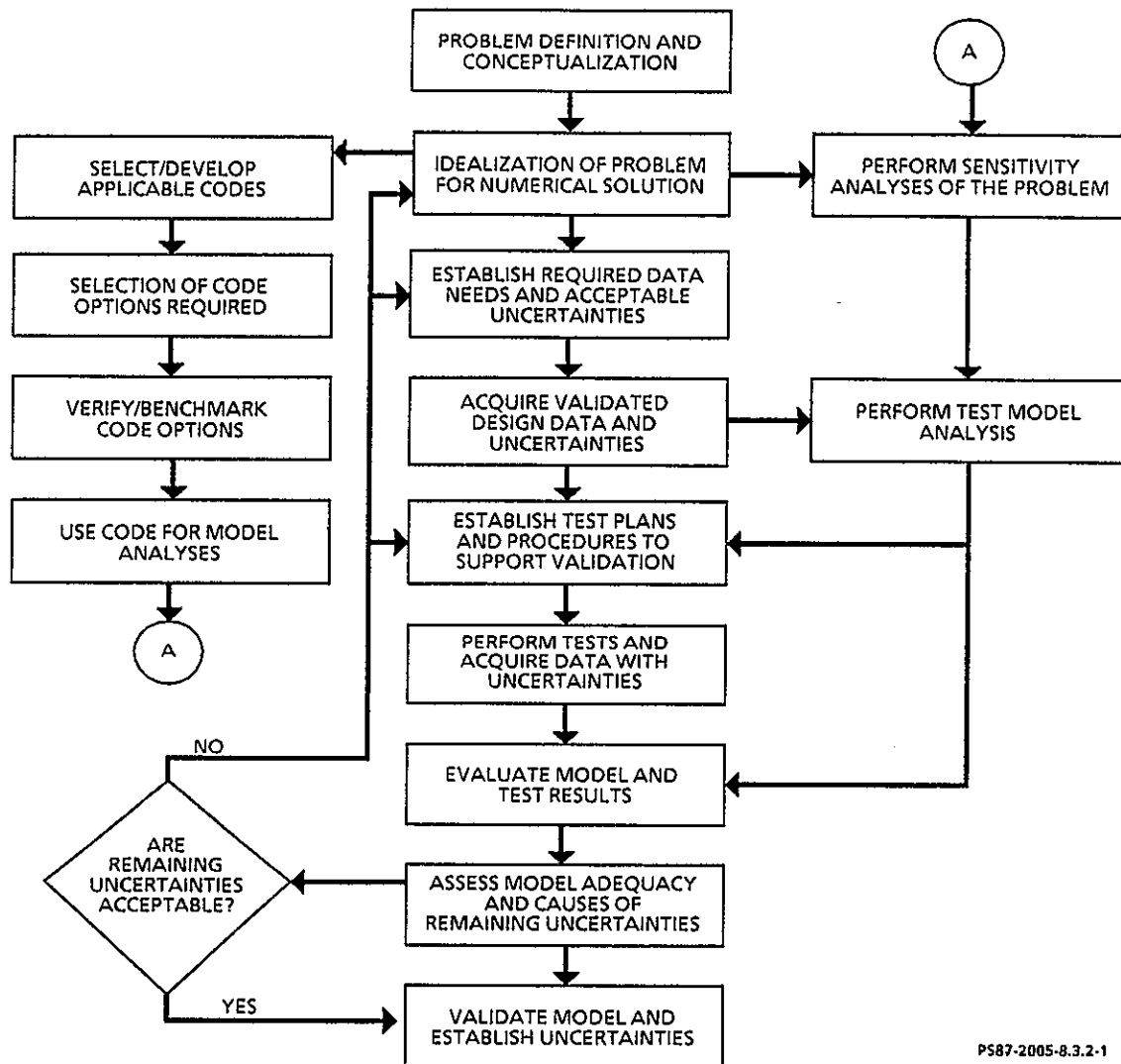
8.3.2.5.2 Rationale

Development of repository models is an iterative process using results of laboratory, field, and design studies. Development of adequate predictive capabilities for methods that have not been generally established in existing standards, codes, or regulations involves a process as identified in Figure 8.3.2.5-1. Initially, the problem to be analyzed must be defined and a solution concept developed. Development of the problem definition begins with the specification of the applicable criteria and proposed system to be analyzed. Then the problem must be idealized based on a number of assumptions and simplifications to allow a numerical solution. This may require generalizations of features such as room shapes, geologic structure, or continuum representation of the jointed rock mass. Following idealization of the problem to satisfy the design assessment needs, identification and selection (or development as required) of applicable computer codes or other analytical tools is made to allow analysis of the problem.

To support resolution of the issues identified in Section 8.2 and to present a complete description of the repository modeling activities necessary to support development of the design, the following investigations have been identified:

- Repository geomechanics models (Section 8.3.2.5.3).
- Additional repository design models (Section 8.3.2.5.4).

A repository geomechanics model consists of three major components: (1) a material model, (2) a numerical model, and (3) a set of boundary conditions. A material model contains the constitutive law for the material behavior and the parameter values. A numerical model is an idealization of the physical process and is described by the analysis techniques adopted and the particular numerical procedure applied. The required boundary conditions,



PS87-2005-8.3.2-1

Figure 8.3.2.5-1. Numerical model development and validation.

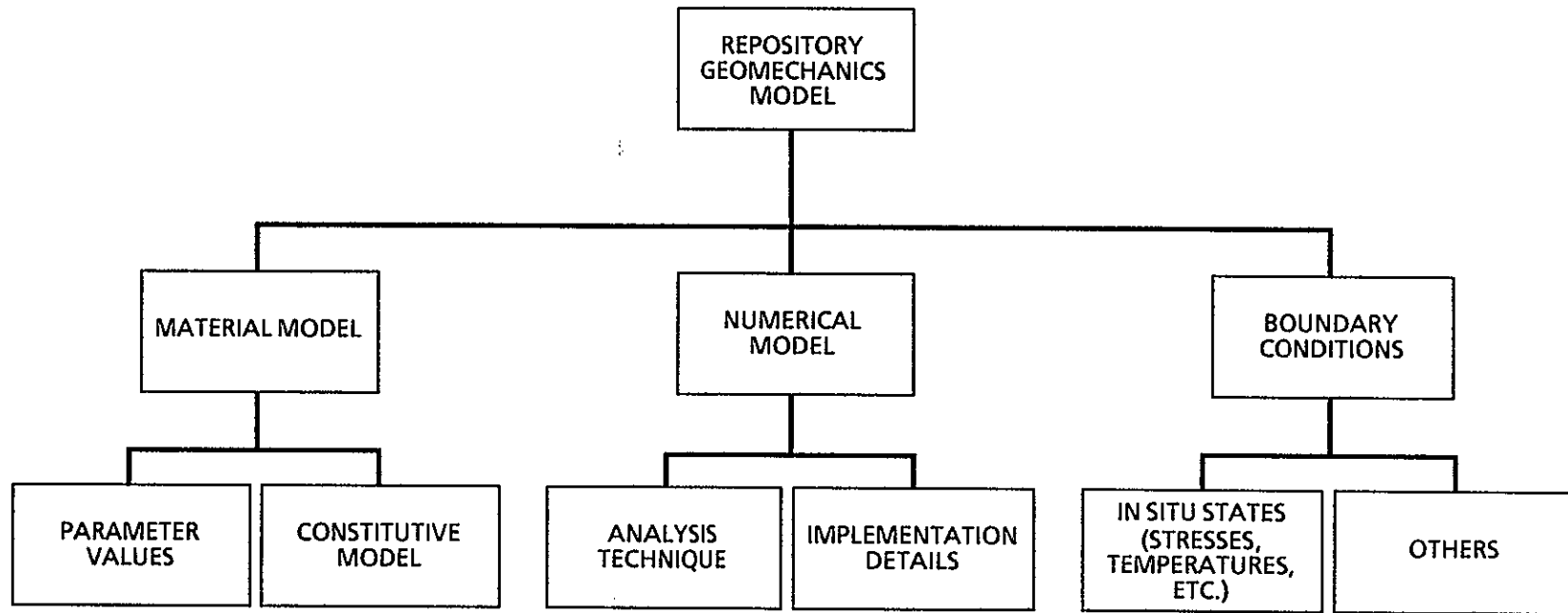
such as in situ stresses, vary between different models. Figure 8.3.2.5-2 illustrates the components of a repository geomechanics model. The number of repository geomechanics models developed depends on the number of material models, numerical models, and boundary conditions considered. The material model, numerical model, and boundary conditions will each be validated as they are developed and the uncertainties in each will be assessed. The uncertainty of the repository geomechanics model depends on these uncertainties and will be assessed as each repository geomechanics model is developed. Validation of the repository models will be made based on the opening performance study.

Repository geomechanics analyses will be conducted to predict the performance of the underground openings during construction, operation, and decommissioning. To conduct the analyses of the expected underground opening performance, it is first necessary to establish an estimate of the relationship between loads applied to the underground structure and deformation in the structure. This relationship is referred to as a constitutive model or constitutive law. The term constitutive law is used in continuum mechanics theory to represent the response of a system to externally applied loads. Constitutive laws are used to represent thermomechanical deformation, fluid flow, and thermal response. For the repository program the primary concern is with the response of the openings to thermomechanical loading. Thus, in this section, constitutive law refers to the unique relationship between stress and strain with consideration given to thermomechanical effects.

The constitutive law is specific for a particular material. Because rock has scale-dependent properties, the model must also be specified with consideration to the structure or opening being analyzed. Thus, constitutive modeling is treated as a structure-dependent input, and the constitutive modeling requirements may differ for the various repository openings (e.g., emplacement boreholes, emplacement rooms). Most of the constitutive models can be described in a set of mathematical equations containing a number of parameters. A material model is established by the selection of a constitutive model and the determination of the parameter values associated with the constitutive model. Specific activities for developing basalt material models are described in Section 8.3.2.5.3.3.1.

Assessment of the expected performance of underground openings during construction, operation, and decommissioning will be based on incorporation of the material models in the geomechanics analyses for the following general areas:

- Thermal analysis--The determination of temperature distributions around repository openings. Temperature distributions are used to verify compliance with maximum temperature standards from the appropriate criteria document and as input into thermomechanical analyses.



PS88-2014-8.3.2-1

Figure 8.3.2.5-2. Components of a repository geomechanics model.

- Mechanical analysis--The determination of excavation induced stresses and deformations. Excavation induced loads are needed for design verification and Exploratory Shaft Facility test planning support.
- Seismic analysis--The determination of the effects of seismic loading on the stress distribution around repository openings. This activity applies only to license application design verification.
- Thermomechanical analysis--The coupling of thermally induced loads and excavation induced loads around repository openings. These analyses provide the primary tool for design verification.
- Sensitivity analysis--The determination of the amount of change in the estimates of a system response that will occur due to variations in input parameters.
- Uncertainty analysis--An assessment of the uncertainty in the estimate of a system response due to uncertainties in input parameters. Uncertainty analysis should follow a thorough sensitivity study and should incorporate the variability of the system, bias in test specimen selection, errors in measurements of the various input parameters, and uncertainty in the analysis method.

Sensitivity and uncertainty methods are used to evaluate the validity of the model predictions. Rock masses may be highly variable in comparison to the normal deterministic model that must use a number of assumptions and conceptual models to simplify and describe the system and processes involved. The assumptions and conceptual models are based on available data and related experience. The subjective nature of this process is a source of uncertainty that must be quantified to the degree possible in order to ensure design requirements are met.

A possible approach to reducing uncertainty in model predictions is the use of hypothesis testing for analyzing the data and evaluating competing conceptual models. The approach requires a clear formulation of each component of the conceptual model or assumption that is then evaluated statistically. If the evaluation of the hypothesis supports a conceptual model component, confidence is increased in that particular interpretation of the data. If the evaluation does not support the conceptual model component, either it must be rejected or additional data must be obtained to determine the applicability of the conceptual model component. This approach results in decisions that can be documented objectively and reviewed to validate the concept or provide a basis for further evaluation.

As the repository design is developed the assessment of performance necessary to support a license application will require the use of validated repository models. Field tests and observations will be used to confirm the adequacy of the repository models. Although test information may be determined over a relatively short time period during site characterization,

the results still help verify the applicability of the assumptions used in the governing model equations and the assumed boundary conditions. Continued evaluation of the system performance to further validate the repository models through performance confirmation during construction and operation of the repository will be required to allow permanent closure of the repository.

8.3.2.5.2.1 Analysis techniques

A wide range of techniques are applicable to the specific analysis problems supporting repository design. The class of problem often dictates the method required to obtain a solution. Geometric complexity, constitutive properties, input/output requirements, and fundamental resources (e.g., time, manpower) will be examined when determining the analysis approach.

Based on the problem to be solved and the data available, a number of specific types of analyses may be appropriate for problem solution. The specific approaches planned for thermal, mechanical, or thermomechanical analyses may involve, as appropriate, any of the following solution methods:

- Finite element.
- Finite difference.
- Boundary element.
- Discrete element.
- Closed form.
- Empirical.

These methods will be used in sensitivity studies, uncertainty analyses and comparative studies, as well as deterministic analyses to supply information necessary for design and performance assessment decisions.

The repository analyses will make use of sensitivity studies to identify the relative importance of the material parameters and boundary conditions used in analyses to support design verification and assessment of repository performance. The results of these studies provide a basis for identifying significant parameters to be obtained during site characterization.

Due to the uncertainties inherent in the description of the host geologic system and the lack of complete confidence in the specification of events (which may evolve slowly or may be catastrophic in nature) that may affect the predicted analysis response, it is especially important to make an estimate of the accuracy of any prediction.

To properly quantify the uncertainty in an estimated response and to identify key parameters, it is necessary to have the following estimates:

1. The amount that the response can be expected to change for a given set of changes in the model input parameters.
2. The degree to which the input parameters can be expected to vary spatially for the Hanford Site and the errors in estimating these parameters from test results.

The first item deals with the sensitivity of the model response relative to input changes. This is established based on sensitivity analyses to identify which model parameters have the greatest potential impact on the response uncertainty. The resulting sensitivity coefficients provide an initial estimate of the relative importance and, thus, priority of site-specific parameters to be acquired during site characterization.

The second item involves quantification of the uncertainty in estimating the analysis input parameters. This includes the engineered system data and site-specific data. Determination of the variability of these input parameters requires estimation of uncertainties due to the following factors:

- Inherent variability of the parameter.
- Method of acquiring data.
- Interpretation and alternative interpretations of data.
- Extrapolation of data for use in analyses.
- Covariances with other parameters.

Test plans for obtaining the necessary parameter estimates must provide the methods for obtaining site-specific data on the parameter variability and interrelationships. The results of the sensitivity analyses and the parameter uncertainty will be used to establish the model uncertainty in predicting response.

To fully quantify the input and output characteristics of a given analysis technique, it is necessary to estimate the uncertainty caused by the following additional factors:

- Systematic errors from approaches, approximations, and simplifications in conceptual models used to represent important physical processes or phenomena.
- Mathematical representation of the conceptual models.
- Numerical implementation of the mathematical models and the resulting accuracy, stability, and range of applicability.

These additional factors are assessed by means of verification, benchmarking, and model validation activities.

8.3.2.5.2.2 Code verification

The requirements of ANSI/ASME (1986) specify that computer programs may be used for design analysis without individual verification of the program for each application, provided that the following have occurred:

- The computer program has been verified to show that it produces correct solutions for the encoded mathematical model within defined limits for each parameter employed.

- The encoded mathematical model has been shown to produce a valid solution to the physical problem associated with the particular application.

Numerical models developed using these verified codes are used to evaluate the relative significance and required measurement certainties for the model variables by conducting sensitivity analyses. Specification of required data is based on these sensitivity analyses. Future model development requires the assessment of the need for stochastic modeling capabilities. Deterministic models used in the design analyses may require modification to allow stochastic assessment of the naturally occurring variability of the rock mass.

To allow the use of general codes for modeling analyses and to supply confidence in the correctness of the analyses, a verification, benchmark, and validation process will be used for all codes and models supporting license application. Project specific implementation of the regulatory position established by Silling (1983) is governed by the BWIP project management plan and subordinate procedures. Necessary documentation for use of the accepted codes in design analyses will result from the following activities:

- Code Verification--Testing of the code options to provide assurance that a computer code correctly performs the operations specified in a numerical model.
- Code Benchmarking--Documented comparison of the results obtained from one code with one or more other codes when applied to solve the same problem. These comparisons help eliminate coding errors and increase confidence in model results.
- Model Validation--Assurance that a model is a correct representation of the process or system for which it is intended.

The use of available codes for design analyses, with modification as necessary to simulate specific geomechanical responses, will require verification and benchmark testing documentation of only the code options actually used.

8.3.2.5.2.3 Model validation

The term "validation" is used to describe the process of judging the adequacy of a model. Validation of a model, in effect, would validate the computer code and the analytical procedure using the code.

Model validation requirements will be established as necessary to satisfy the requirements of ANSI/ASME (1986) for all analyses used in support of license application. Validation requirements are established as necessary with consideration that validation documentation may not be required for design analyses that are adequately coded and may be required for uncoded

analyses that pertain to performance and are important to waste isolation or to safety per the established safety classification for the system, subsystem, or component.

Specifications for validation activities will be established in development of the analysis activities identified in the repository modeling investigations.

An initial step in validation is a comparison of model results with performance results from other similar engineering activities. This provides a qualitative comparison to generally assess the level of applicability of the model. Poor performance at this level may preclude more sophisticated comparisons until model corrections can be made or an adequate model developed.

A higher level of validation comes from dedicated tests in the Exploratory Shaft Facility and the initial phases of construction monitoring where quantitative measurements are available for comparison with predicted behavior as presented in Section 8.3.2.2.3 on evaluation of opening performance and stability. Dedicated field tests are used for validation at both a canister scale and a room scale. Models of rock mass strength, deformability, and permeability, as well as testing methods and boundary conditions will be examined at this stage. For example, full-scale heater tests can be used to provide information for validation of thermomechanical models.

The final validation will be provided by the long-term confirmation of the total repository performance. The repository performance will be monitored by observation of behavior during construction and operations. Part of this confirmation will take place in a dedicated, prototypical repository area, where a number of observations will be made over a long period of time. Periodic checks of the deformation of the underground openings in other parts of the facility will be possible over moderate lengths of time. Indirect monitoring by geophysical methods and waterflow measurements will augment and extend observations over a longer timeframe and larger area. Confirmation of this nature is largely qualitative and primarily intended to indicate variances from acceptable performance over the design life of the repository.

The modeling and design process in which a verified computer code used in a modeling scheme is subjected to progressively more rigorous cross-checking, is fundamental to the development of confidence in the prediction of repository performance. Models will be planned so that validation and confirmation are not only necessary features, but are also reasonably attainable goals. Reliance will be placed on models only to the extent that the models can be validated.

8.3.2.5.3 Investigation of repository geomechanics models

This investigation will provide geomechanical models for use in assessing the stability of repository openings. Mechanical and thermomechanical analyses will be used to evaluate opening deformations and loads on system components for selection of design alternatives. Effects of dynamic loading due to seismic events will also be assessed. This information is needed to resolve Issue 2.7, preclosure performance; Issue 4.2, ensuring worker nonradiological health and safety; and Issue 2.7, retrievability.

8.3.2.5.3.1 Purpose and objectives

The purpose of this investigation is to provide geomechanic models of sufficient accuracy to conduct predictive analyses of the repository opening performance. These models will be used with the data obtained to satisfy the information needs listed in Table 8.3.2.2-1 to conduct the predictive analyses to support selection of appropriate design alternatives.

Principal design objectives and elements of the nuclear waste repository in basalt that require the use of geomechanical models include the following:

- Waste emplacement configuration, including hole spacing, drift shapes, and other geometric parameters.
- Ground support selection and design.
- Overall repository layout.
- Definition of initial and continued monitoring requirements.
- Engineered radionuclide barriers, such as waste packages and seals.

These objectives and principal elements encompass many individual design elements. To accomplish the design objectives, computational models will be developed to analyze specific design problems related to the performance of the repository openings. The repository geomechanics analyses have been identified for the following repository components:

- Shafts.
- Pillar and service openings.
- Emplacement rooms.
- Emplacement boreholes.
- Intersections.

Each of these components are addressed in the activity descriptions of this section.

Development of the geomechanics models for these components is dependent on establishing a material model that can adequately model the thermo-mechanical response of the rock mass due to excavation and operation of a

repository. This involves the initial activity in this investigation to estimate the relationship between loads applied to the underground structure and deformation in the structure (constitutive model).

8.3.2.5.3.2 Rationale

Geomechanics modeling for the BWIP will employ both empirical and analytical techniques to examine performance issues. Site characterization provides the parameters (e.g., material properties, in situ conditions, and other site data) from which a concept or prototype is created. The prototype is then analyzed and interpreted taking into consideration the limitations of the input data, initial assumptions, and the modeling technique.

Modeling provides a basis for repository design decisions by the following means:

- Performance prediction--Models are used to predict short- and long-term behavior of underground openings and the near- and far-field rock mass response. Stability, rock support, and safety are analyzed based on these models.
- Scoping studies--Analyses of systems are performed using variable conditions to compare alternative configurations and determine constraints for the selection of a repository layout.
- Sensitivity analyses--Model studies are conducted in which certain parameters are varied to assess their relative influence and to help understand the effects of uncertainties in data collection and analyses. Also, assessments of expected ranges of response are required for the design of in situ tests and the planning of instrumentation.

Development of valid models requires incorporation of an appropriate material model to accomplish the goal of the repository geomechanics modeling activities. The first step in the development of a material model is to establish a suitable constitutive model.

The term constitutive model refers to a unique relationship between stress (σ) and strain (ϵ) for a particular material. The simplest form of a constitutive model is the linear Hooke's law $\sigma = E\epsilon$, where E is Young's modulus. More sophisticated models can be defined to include nonlinearity, anisotropy, yielding, viscous flow, time-dependent behavior, and temperature-dependent behavior. The constitutive model is specific for a particular material. Because rock has different properties depending on the volume of rock under observation, the model must also be specified with consideration to the structure or opening being analyzed. In addition, certain analyses may require a greater level of sophistication than others. Because of these factors, constitutive modeling is planned to be treated as structure-dependent input, and hence the constitutive modeling requirements may differ for the various repository openings.

Specific activities for developing basalt material models are described in the studies for this investigation and the use of the site specific data on the geomechanical characteristics of the host rock in Section 8.3.2.2.3. The development of a material model is an ongoing process. A material model for advanced conceptual design and a refined model for license application design are planned to be issued. The advanced conceptual design model will be based on data gathered prior to exploratory shaft testing. The license application design model will incorporate additional laboratory and field data and discrete element modeling results.

The following are general types of data needed for the material model:

- Rock mass strength.
- Rock mass deformability.
- Thermal properties.

Material model development will be based on an approach involving a study of available test results, review of existing material models, postulation of alternative constitutive models, and a comparative study to establish an appropriate model for design analyses. Validation of the material model will be provided by confirmatory testing in the Exploratory Shaft Facility.

8.3.2.5.3.3 Description of studies and activities

The repository geomechanics analysis investigation is composed of the following activities:

- Material model development study.
- Shaft modeling.
- Pillar/service opening modeling.
- Emplacement room modeling.
- Emplacement borehole modeling.
- Intersection modeling.

The material model development is a study involving characterization of the rock mass behavior. The other modeling activities will incorporate the material models developed in this study into numerical models used in assessing opening deformations and stability.

8.3.2.5.3.3.1 Material model development study.

The goal of the material modeling study is to develop a material definition that will adequately describe the behavior of the rock mass. All of the analysis codes that will be used in repository modeling have certain constitutive laws built in, and it is only necessary to define the parameters for a particular material. The use of one of the existing constitutive laws would save a considerable amount of programming effort, time, and expense. Therefore, the models that exist in the various codes are being examined to determine their applicability to basalt modeling as detailed in the Study Plan for Material Model Development (Donovan, 1987).

This study initially consists of an evaluation of existing constitutive models. To date, one constitutive model has been identified that may provide a better representation of repository conditions than the existing models. This model, based on the continuous damage mechanics theory of Resende (1985), is incorporated in an existing version of ABAQUS (Hibbitt et al., 1985). Other available damage models will also be evaluated.

Other alternative models may be postulated in the future. None have been defined as of this date. Because of the time required for coding, installation, and checkout of code modifications, the continuous damage model and any other alternative models will be evaluated for use in license application design verification only. Data necessary to develop the parameters for these models will be obtained from the site characterization testing as discussed in Section 8.3.2.2 with the parameters listed in Table 8.3.2.2-3.

Several material models have been identified for evaluation in this activity. Others may be included as a more thorough evaluation of existing and alternative models is made. The material models identified thus far are given below:

- Linear elastic model--Simplest constitutive model; requires only two input parameters; does not account for any yielding in the rock mass; may be sufficient if rock mass strength is high enough to prevent yielding, or if stress redistribution due to yielding is minimal.
- Elasto-plastic models--These models assume elastic behavior up to yielding. The yielding criteria considered may include the Mohr-Coulomb criteria, the Drucker-Prager criteria, the BWIP rock mass strength criteria (Section 2.3.3.2), or others.
- Nonlinear models--These models assume nonlinear elasticity with a yield criteria. Two examples are concrete models and the continuous damage model.

A major activity in the development of the material model is the use of discrete element analyses for obtaining a basalt material model. This effort is intended to produce an equivalent continuum stress/strain relationship, and its associated parameters, that can either be programmed into one of the analysis codes or incorporated into one of the existing material models.

The approach adopted for discrete element modeling is to analyze assemblages of rock blocks under simple loading conditions. The spacing and orientation of the joints between the blocks and the mechanical properties of the joints will be varied. The relationship of stress versus strain will be determined for each analysis. In this way, effects of scale, joint orientation, and joint spacing on the stress/strain curve can be demonstrated. The constitutive behavior predicted using the discrete element models will be compared with the continuum models available in the large analysis codes to arrive at an adequate continuum model.

The material model developed will be incorporated into the finite element or boundary element analyses as equivalent continuum models. The models thus developed will be validated by confirmation testing in the Exploratory Shaft Facility. Following development of the initial material model, preliminary modeling of the mine-by and Exploratory Shaft Facility openings will be conducted using the equivalent continuum models. These models will aid in the final design of the Exploratory Shaft Facility to identify appropriate data needs. As-built models of the other exploratory shaft tests will be analyzed for final validation. Comparisons of measured displacements in the Exploratory Shaft Facility and computed displacements at measurement locations are planned to be made to validate the model. In the event that the models selected do not compare favorably with the test measurements, additional refinement of the model evaluation of anisotropy and scaling of the material properties will be made. Additionally, further experiments may be necessary to help in validation of the final material model.

Since confirmatory testing in the Exploratory Shaft Facility will occur late in the design development, it is planned to consider more than one material model through to the validation phase. The models will likely include a simplified model, such as Drucker-Prager or linear elastic and a more complex model, such as the continuous damage model. In this manner, there will be an increased probability of establishing an acceptable model.

8.3.2.5.3.3.2 Shaft modeling.

Modeling of repository shafts will be carried out in activities supporting the design decision process to verify the compliance of the shaft design with design criteria given in the appropriate criteria document. Specific geomechanics analyses of shafts identified to date are summarized in this section. For this activity, the term shaft will refer to the shaft exclusive of the effects of the shaft station. The shaft station will be analyzed as indicated in the intersection modeling activity in Section 8.3.2.5.3.3.6.

The geomechanics analyses of the shafts will be limited to assessing the shaft stability. Additional design considerations will require incorporation of other factors such as ventilation, hoisting, materials transport, and personnel requirements in shaft design. These additional repository design models are discussed in Section 8.3.2.5.4.

Shafts are difficult to analyze due to the presence of numerous geological layers in a vertical section and the highly anisotropic initial stress state. A significant portion of the time devoted to shaft modeling will be spent developing a reliable analysis approach. It will be necessary to determine whether or not acceptable results can be obtained given certain simplifying assumptions. Criteria for evaluating alternative approaches need to be established.

Geomechanics design issues relating to shafts that will be modeled include the following:

- Effects of layered geologic media on shaft stability.
- Effects of anisotropic initial stresses.
- Shaft liner stability.
- Sensitivity studies to determine the effect of uncertainties in the material properties on the construction and stability of the shaft.
- Kinematically unstable blocks falling out of the shaft wall during construction.
- Effects of seismic loading on shaft stability.
- Effects of groundwater on the shaft.

Geomechanical design concerns relating to shafts will be divided into two basic models--shaft stability and shaft liner models.

The shaft stability models will be based on two-dimensional axisymmetric or three-dimensional geometric mesh under various loading conditions (e.g., layered rock, initial state of stress, shaft liner weight, and seismic loadings). Use of the axisymmetric model will be to approximate the loading response but may neglect several important mechanisms influencing the shaft behavior.

The shaft liner models will be developed using three-dimensional finite element models to assess the support and rock interaction considering the effects of shaft out of roundness, shell stiffeners, welding effects, uneven grout load, operating loads, external pressure, and compression loads.

8.3.2.5.3.3 Pillar/service opening modeling.

For this activity, the pillar area is assumed to mean the shaft and service openings between the main emplacement areas. Modeling will be carried out for the purpose of verifying the design of the pillar and the service openings contained in the pillar area. Design criteria will be provided in the appropriate criteria document.

The following analyses have been identified for pillar design:

- Thermomechanical analysis of repository heating effects on pillar stability.
- Thermomechanical stress analysis of various opening geometries present in service area.

Additional analyses may be identified during the advanced conceptual design phase.

In a system of underground openings in which no artificial support (e.g., linings, sets, props) is used, the weight of the overlying cover is sustained on areas of unexcavated rock lying within the boundaries of the openings, which are referred to as pillars. These pillars constitute the most important structural elements in a system of openings, and the determination of pillar stress is required in the evaluation of their stability.

Pillar/service openings will be analyzed using either two-dimensional or three-dimensional finite element models. Different opening shapes will be modeled to evaluate the stability of the pillars and openings. Thermal loading will be included to determine the effect of total loadings on the openings. However, some openings may not require including the effect of thermal loading if their locations are far from the heat sources.

8.3.2.5.3.3.4 Emplacement room modeling.

Analyses will be carried out to verify the compliance of the emplacement room design with criteria given in the appropriate criteria document. Emplacement room components that will require analysis are as follows:

- Excavation sequence analysis for verification of design suitability during construction and operation phases.
- Sensitivity studies to determine effects of variations in material properties and room shapes.
- Temperature distributions required for verification of compliance with maximum temperature standards.
- Thermomechanical stress distribution required for design verification.
- Analysis of emplacement room stability under anomalous geologic conditions (changes in dense interior thickness, major discontinuities intersecting emplacement room, vesiculation in dense interior).
- Adequacy of artificial rock support design.
- Effect of seismic loading on emplacement room stability.

Results of these analyses will be used in assessment of the changes in the fluid flow for hydrologic analyses in the near field. These hydrologic assessments support radionuclide transport analyses discussed in Section 8.3.5.2, Strategy for postclosure performance assessment.

Emplacement rooms will be modeled using a two-dimensional plane mesh by using either finite element or boundary element codes. Thermal loads will be included. The in situ state of stress will be the only mechanical loading.

8.3.2.5.3.3.5 Emplacement borehole modeling.

Analysis of emplacement boreholes will be conducted to verify compliance of the borehole design with criteria established in the applicable criteria document. Specific problems requiring analysis are as follows:

- Thermal distributions around boreholes.
- Excavation induced stresses.
- Coupled thermal/mechanical loading.
- Sensitivity studies to verify compliance under potential variations in material properties.
- Uncertainty analysis.
- Analysis to determine effects of potential anomalous geologic structures on borehole stability (dense interior thinning, vesiculation in dense interior, presence of major discontinuities intersecting boreholes).
- Effect of seismic loading on borehole stability.

The emplacement boreholes will be modeled by a simple two-dimensional plane symmetric mesh using either the finite element or boundary element method. The borehole analysis will assess the effects on single and multiple boreholes. Analyses of the stress and temperature effects on the borehole collar will be conducted as intersection analyses described in the following section. Thermal transient loading will be modeled to simulate the nuclear waste behavior in the emplacement borehole. Packing material surrounding the borehole will be included to appropriately evaluate the rock temperature in the very near field of the borehole. The in situ state of stress will be applied for the excavation sequence analysis.

Nominal values of material properties for rock, packing, and spent fuel will be used. Sensitivity studies have been performed to determine the responses of the rock mass due to the range of uncertainties for these properties.

Further analyses will be performed to determine the borehole response by including the rock joints in the rock mass surrounding the borehole and considering the effect due to material property variations in the rock immediately around the borehole. An elastic-plastic analysis will also be performed to determine the potential areas of overstress around the borehole. These analyses will also support assessment of hydrologic effects in the near field.

8.3.2.5.3.3.6 Intersection modeling.

Because of the complex geometry and the need for three-dimensional analysis methods, design verification of intersections has been identified as a discrete activity. The following types of intersections will be considered:

- Borehole/room intersection.
- Room/access drift intersection.
- Shaft stations.

The analysis of these components will, of necessity, be three-dimensional. Model development will involve a significant amount of the work in this area due to complex geometries and large transition areas. The model will cover at least the geometry of the borehole where the heat source originates. Intersections will be modeled with a refined mesh to obtain reasonable responses and accurate results. Because there is no analytical solution to verify the model, it is essential that the model will be checked against the same model running on different codes.

A three-dimensional in situ state of stress will be applied. Various opening shapes may be modeled to evaluate their stabilities. Thermal loads will be included for those areas that will have a significant temperature change. The in situ state of stress will be the only mechanical loading.

8.3.2.5.3.4 Application of results

As previously indicated, the results of the material model development will be incorporated into the finite element or boundary element analyses as equivalent continuum models for use in assessing repository performance.

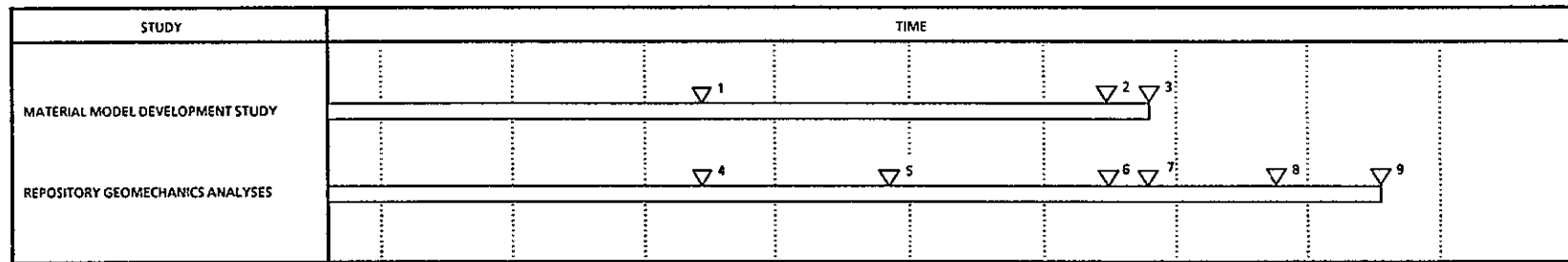
These modeling activities will provide a basis for decisions on the selection of an appropriate repository design and for assessment of the expected performance of the repository openings.

8.3.2.5.3.5 Schedule and milestones

Repository design modeling activities are tied to the key design milestones. Verification of both the advanced conceptual design and license application design will be made. Model development for these verification activities will begin at the start of each design phase. The schedule for this model development is shown in Figure 8.3.2.5-3.

Material modeling activities are planned to produce a model for advanced conceptual design and a refined model for license application design. The material models for design verification will be provided prior to 60% completion of the design.

Validation of the repository models is tied to completion of the mine-by test in the Exploratory Shaft Facility. Final design verification with a validated material model will occur after completion of these validation activities.



PS08-2014-0.3.2-5

- ▽¹ PROVIDE MATERIAL MODEL FOR ACD ANALYSES.
- ▽² OBTAIN DATA FROM CONSTRUCTION OF ES AND BEGIN CONFIRMATION OF MATERIAL MODEL.
- ▽³ PROVIDE MATERIAL MODEL FOR LAD ANALYSES.
- ▽⁴ OBTAIN MATERIAL MODEL FOR ACD ANALYSES.
- ▽⁵ PROVIDE ASSESSMENT OF ACD STABILITY.
- ▽⁶ OBTAIN DATA FROM CONSTRUCTION OF ES FOR BOUNDARY CONDITIONS AND INITIAL CONFIRMATION OF RESPONSE PREDICTIONS.
- ▽⁷ OBTAIN MATERIAL MODEL FOR LAD ANALYSES.
- ▽⁸ OBTAIN RESULTS FROM ES TESTS FOR BOUNDARY CONDITIONS AND COMPONENT RESPONSES.
- ▽⁹ PROVIDE REPORT ON ASSESSMENT OF LAD STABILITY.

ACD = ADVANCED CONCEPTUAL DESIGN
 ES = EXPLORATORY SHAFT
 LAD = LICENSE APPLICATION DESIGN

Figure 8.3.2.5-3. Schedule for repository model development.

8.3.2.5.4 Investigation of additional repository design models

In addition to the geomechanical modeling, other models are necessary to develop and support the repository design of the surface facilities, the shafts and the underground facilities. Required models for this investigation include those for the design disciplines, operations, and system analysis. Special emphasis will be placed on underground ventilation, geohydrology (water and gas inflow), scheduling, and cost estimating. These models support the design development activities identified in Section 8.3.2.4 as well as resolution of the issues.

8.3.2.5.4.1 Purpose and objectives

The purpose of this investigation is to provide models, in addition to the geomechanics models described in Section 8.3.2.5.3, necessary to develop an appropriate, safe, and cost effective repository design. Specific objectives include the following:

- Overall repository layout.
- Definition of initial and continued monitoring requirements.
- Development of operations schedules.
- Logistics for construction and operations.

This section identifies the additional repository design models necessary for development and support of the design.

8.3.2.5.4.2 Rationale

Development of a complete design of the repository will be supported by a number of engineering activities that will require the use of models. These modeling activities are presented in terms of the analyses necessary to support (1) design of surface facilities and equipment and (2) design of underground facilities and equipment including shafts. The analyses to support underground facilities and equipment design are those necessary for planning construction and operations needs. Advances in applicable modeling techniques will be incorporated in the design process with code verification and model validation conducted as described in Sections 8.3.2.5.2.2 and 8.3.2.5.2.3.

Development of interrelated computer models to support these design activities will result from the following activities.

8.3.2.5.4.3 Description of activities

During advanced conceptual design and license application design a number of models will be used in evaluation and selection of appropriate alternatives for eventual construction, operation, and decommissioning of a repository. The following activities briefly describe these models:

- Surface facilities and equipment modeling.
- Underground facilities and equipment modeling.

Each of these studies is composed of a number of modeling and analysis activities.

8.3.2.5.4.3.1 Surface facilities and equipment modeling.

A number of numerical and computer aided modeling capabilities are necessary for the design of individual surface systems. The basic modeling areas are design, operations, and system evaluation, as detailed in this section.

8.3.2.5.4.3.1.1 Design models. Models are required to support the activities of engineering design. Output from these models will be used to define the design components of the repository surface facilities. Individual design disciplines and model applications for each are listed in Table 8.3.2.5-1.

During conceptual design, most of these design objectives can be achieved by hand calculations and drawings to yield basic layouts and line diagrams. However, as the need for comparison, checking, and quality assurance increases the complexity of design, better solutions are required. Transfer of applicable design modeling to interactive computer codes will result in development of an integrated design product. Codes to support most of the discipline items in Table 8.3.2.5-1 are currently available.

8.3.2.5.4.3.1.2 Operations models. Modeling of the various surface operations is necessary to determine the appropriateness of design with regard to operations performance. Operations models are used to develop site specific designs and schedules necessary to establish the appropriateness of proposed operating methods and equipment. Operational procedures can be checked and corrected in advance of implementation.

Surface operation activities suited to computer modeling are shown in Table 8.3.2.5-2. Some overlap of capabilities may exist with some of the above models, but each is sufficiently unique to require separate solutions that may or may not support the functions of other models.

Table 8.3.2.5-1. Surface facilities modeling requirements for design

Discipline	Modeling application
Electrical	Electrical network, routing, loading, design, and list of materials
Piping	Piping network, routing, loading, design, and list of materials
Heating, ventilation, and air conditioning	Heating and cooling network, routing, loading, design, and inventory primarily for surface buildings
Structural	Design of structures and buildings
Architectural	Layout and arrangement design of surface facilities through computer-aided design systems
Mechanical	Network, routing, and design of mechanical systems to include bins, chutes, and conveyors
Civil	Earthwork, access, and routing design
Instrumentation	Design of systems for monitoring, process control, and fire protection
Environmental	Design of environmental monitoring systems, analyses of nuclear and nonnuclear airborne release and dispersion
Nuclear	Design of all systems related to or associated with nuclear waste handling, including criticality and shielding analyses, onsite and offsite release scenarios
Geotechnical	Analyses of seismic response
Mining	Design input to mine services support systems (e.g., head-frames and structures)
Hydrology	Surface hydrology for analyses of surface flooding potential and control

PST87-2005-8.3.2-21

Table 8.3.2.5-2. Surface facilities operations modeling requirements

Discipline	Modeling application
Haulage	Transport of mined rock from headframe bins to storage pile, etc.
Waste handling	Scheduling and processing of waste from receipt to delivery at shift conveyance
Traffic control	Queuing analysis, transport facilities, sizing, route scheduling, and networking
Supply	Commodities routing, storage, and quantity analysis
Security and surveillance	Scenario modeling, reaction response, and execution timing
Personnel	Quantities, disciplines, and statistical effects
Maintenance	Scheduling and response for planned and unplanned maintenance activities

PST87-2005-8.3.2-22

During conceptual design, a majority of these modeling tasks can be performed using simple models to give average or global values and line diagrams. Transfer of these models to computer codes will be made to improve their applicability in supporting design development. Operations computer models introduced during conceptual design will be verified and validated as necessary during the license application design development to provide maximum support to this design phase.

8.3.2.5.4.3.1.3 System evaluation models. Prior to construction or installation, the expected behavior of the overall surface facility and individual systems must be modeled. In particular, the systems listed in Table 8.3.2.5-3 must be examined.

Support of system evaluation during the advanced conceptual design will use simple models such as subjective analysis and calculation of global values. Basic design decisions will be made using these analysis results. During license application design, installation of computer models for system evaluation will be necessary.

8.3.2.5.4.3.2 Underground facilities and equipment modeling.

Additional modeling must be performed for the underground facilities including shafts. Some of this modeling is unique to the underground environment while other models are sufficiently similar to surface counter parts that only limited modifications are necessary. Underground modeling requirements and their comparison to the surface modeling are as follows.

Table 8.3.2.5-3. Surface facilities modeling requirements for systems evaluation

Discipline	Modeling application
Nuclear release	Onsite and offsite release scenarios
Nonnuclear airborne materials	Dispersion, release, drift, and shadow patterns of particulate matter under various atmospheric conditions
Monitoring	Evaluation of monitoring systems, atmospheric, and near surface
Safety and health	Evaluation of health and safety measures as they relate to and affect personnel and environment
Nuclear	Operational performance evaluation of systems directly involved with the handling of nuclear waste
Engineered systems	Performance evaluation of seismic, wind, and fatigue effects

PST87-2005-8.3.2-23

8.3.2.5.4.3.2.1 Ventilation modeling. Programs are needed to model the ventilation networks and the resultant environment in the underground repository. Such modeling defines the effects of the repository layout on the airstream and environmental characteristics associated with the ventilation network. This type of modeling is necessary to confirm the adequacy of ventilation system components under all plausible operating scenarios. Modeled effects will include:

- Pressure.
- Friction loss.
- Shock loss.
- Velocity.

Required input to the ventilation modeling process includes:

- Length of cross section of each ventilated segment.
- Virgin rock temperature.
- Heat-of-equipment inputs, refrigeration capacities.
- Humidity.
- Directional changes of airflow.
- Friction coefficient.
- Ambient air properties at surface.
- Diesel exhaust and other gases.

- Elevation of each ventilated segment.
- Any additional data that helps to further define the conditions of openings during modeling.

The output from the modeling will provide input to the selection of fans, stoppings, bulkheads, and airflow control and conditioning units. Proper drift sizing and finishing, and airflow routing, will also be addressed. Information will also be available to evaluate the worker environment as discussed in Sections 8.3.2.7 and 8.3.2.8.

During advanced conceptual design development, it is sufficient to model segments of the design layout. Such segments will involve an individual drift or emplacement room, a small portion of the layout, or a simplified intake/exhaust network.

Ventilation modeling will require a more dynamic approach during license application design development with network and environment functions being interactive. The entire subsurface repository, including shafts, will be modeled.

8.3.2.5.4.3.2.2 Water and gas inflow modeling. Modeling of water and gas inflows is necessary to provide input to the design of ventilation, pumping, and emergency safeguards. Inflow data are important because of their effect on the environmental conditions.

For development of the advanced conceptual design, localized water inflow will be considered in addition to average values in estimating potential flooding and gas concentrations.

Inflow modeling complexity, because of its reliance on host rock data over the entire area of the repository, will be limited in its scope until actual in situ measurements are available. Upgrading of inflow data during license application design will be limited to an average value for the entire repository or to a set of values for zones within the repository. Such values will be based in part on the results of work done in the exploratory shaft test facilities at the repository horizon. This data will be the basis for evaluation of the applicability of the hydrologic codes expected to be available. These are discussed in the performance assessment program plan (Section 8.3.5) and included in Tables 8.3.5-7 through 8.3.5-10.

For completion of a final design, the complexity of inflow modeling will increase to require reasonably accurate isopleth information for the entire subsurface site. However, codes to produce such a model should be in place during the license application design phase.

8.3.2.5.4.3.2.3 Hoisting system modeling. Modeling of the hoisting system is necessary to support the accurate scheduling of the repository development and safe, sufficient ingress and egress to the repository horizon. Both surface and subsurface operations and equipment requirements are affected

by the ability of the hoisting systems to transport mined rock, personnel, and supplies between the surface and subsurface. Analysis of the waste hoisting system will require increasing detail as design proceeds.

Determination of hoisting requirements can initially be made with hand calculations, but the need for timely system comparisons requires the use of computer based solutions for hoisting requirements. An accurate and flexible hoist simulation model will be in place prior to completion of advanced conceptual design for use in license application design development.

8.3.2.5.4.3.2.4 Facilities design modeling. Besides the previously discussed modeling activities, specific design disciplines engaged in the subsurface portion of the repository design will require modeling support. These disciplines and their planned modeling applications are listed in Table 8.3.2.5-4.

Simple models and independent computer codes have been used in the early stages of design. Development of the license application design requires the integration of selected analyses for portions of the underground facilities design. The approach for integration of these analysis will be developed during advanced conceptual design.

8.3.2.5.4.3.2.5 Operations modeling. Operations modeling for the underground portion of the repository can be quite different than that required for the surface, because of the difference in the operating environment and the types of equipment and systems used. The planned operations modeling applications are listed in Table 8.3.2.5-5. Where similarities between the underground and the surface operations analysis exist, duplication of effort will be eliminated and a single suitable model applied.

While hand calculations are used for the conceptual design phase, preliminary work for computer-based modeling to support underground design analysis will begin during advanced conceptual design. Initiation of these models will ease the transition to the more complex analyses for license application design.

8.3.2.5.4.4 Application of results

Results from the analyses using these developed models will be used to develop details of the repository design. These analyses will cover the areas identified above to support advanced conceptual design and license application design.

8.3.2.5.4.5 Schedule and milestones

The modeling activities will be conducted to support the development of the repository advanced conceptual design and license application design.

Table 8.3.2.5-4. Underground facilities modeling requirements for design

Discipline	Modeling application
Electrical	Electrical network, routing, loading, design, list of materials, and underground environment considerations
Piping	Piping network, routing, loading, design, list of materials, and underground environment considerations
Structural	Design of steel and concrete supports used in the underground to include rock support, shaft support and lining, and equipment support
Mechanical	Design support to equipment and systems installed in the shaft pillar and along the entries and returns
Heating, ventilation, and air conditioning	Localized design support for offices and shops within the shaft pillar
Instrumentation	Design of systems for monitoring and process control, underground environment conditions, fire protection, and monitoring of the rock mass and emplaced waste
Environmental	Design support to ventilation and instrumentation
Nuclear	Design of nuclear waste handling and transport systems in conjunction with mechanical. Also, design support to environmental, geotechnical, and instrumentation
Mining	Design of repository layout to accommodate construction and emplacement operations, maintenance of access, and determination of excavated quantities

PST87-2005-8.3.2-24

Table 8.3.2.5-5. Underground facilities operations modeling requirements

Operation	Modeling application
Haulage and transport	Haulage of excavated rock from the face to the skip pocket. Transport of materials and supplies.
Waste handling	Handling and emplacement of waste from the shaft collar to emplacement hole.
Security	Scenario modeling and reaction, response, and execution evaluation and timing.
Traffic control	Queuing analysis, facilities involved, sizing, route scheduling and networking with special support for haulage, transport, and waste handling.
Supply	Commodity routing, storage, and quantity analysis.
Blasting	Blasting design of efficiency of rock excavation and control of rock damage beyond openings.
Monitoring	Performance of monitoring systems for both airborne and waterborne materials.

PST87-2005-8.3.2-20

8.3.2.6 Specific program for waste retrieval

Section 8.3.2.6 defines the waste retrieval strategy to be incorporated into the waste package and repository designs and identifies the necessary equipment development and demonstration testing to support these designs. Both the strategy and equipment development are in compliance with the DOE Position on Retrieval and Retrieval for a Geologic Repository (DOE, 1985a). This section is linked to Issue 2.4 in Section 8.2.2.2.4 where the site characterization parameter needs for retrieval are defined. The specific program for waste retrieval is discussed in the one investigation and two subordinate engineering activities that follow.

Background

The requirements for retrievability are delineated in 10 CFR 60.111(b) and 10 CFR 60.133(c) (NRC, 1987a) and in the Nuclear Waste Policy Act of 1982 (NWSA, 1983). The following is stated in 10 CFR 60.111(b):

1. The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 yr after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.
2. This requirement shall not preclude decisions by the Commission to allow backfilling of part or all of (or allow permanent closure of) the geologic repository operations area prior to the end of the period of design for retrievability.
3. For purposes of this paragraph, a reasonable schedule for retrieval is one that would permit retrieval in about the same time as that devoted to construction of the geologic operations area and the emplacement of waste.

10 CFR 60.133(c) states the following:

The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of Section 60.111.

As noted in the Environmental Assessment (DOE, 1986a), Section 122 of the Nuclear Waste Policy Act of 1982 (NWSA, 1983) mandates that the repository shall be designed and constructed to permit retrieval of any waste emplaced in the repository during an appropriate period of operations. There are two

reasons the NRC or the DOE can order the retrieval of any or all of the waste emplaced in the nuclear waste repository in basalt: (1) protection of public health and safety and the environment (NRC-issued order), and (2) recovery of resources (DOE-issued order).

All other operations in which emplaced waste is moved, relocated, or transported to another area of the repository for reasons other than public health and safety (and environment) or for recovery of resources are not considered retrieval. In the BWIP Retrieval Strategy, retrieval is complete when the waste reaches the surface of the repository. The repository operations area will be designed so the emplaced waste could be retrieved on a reasonable schedule, starting at any time up to 50 yr after waste-emplacement operations are initiated, unless a different time period is specified by the Secretary of the DOE and approved by the NRC. For design purposes, it is assumed that the actual retrieval would take approximately as long as waste emplacement and repository construction. This time is consistent with 10 CFR 60, which requires public health and safety considerations be of prime importance in waste retrieval operations.

The position on retrievability and retrieval, as documented in the Generic Requirements for a Mined Geologic Disposal System, Appendix D (DOE, 1986b) provides the general requirements for retrieval and retrievability for use in the siting, design, operation, and decommissioning of a repository. The position paper specifies the period of retrievability; states the reasons for retrieval; and describes and documents design, construction, operation, and maintenance equipment requirements for the retrieval of waste from an operating repository. An evaluation of the effects of these requirements on the repository design and the associated equipment needs has not been completed. These retrieval effects would be analyzed and addressed during site characterization and subsequent design phases supporting the license application.

The BWIP has prepared a strategy to ensure compliance with the DOE position on retrievability and retrieval. This strategy identifies the various retrieval scenarios that have been postulated, the condition of the repository at the time of retrieval, and the proof-of-principle testing that will be completed to demonstrate that the retrievability issue is fully satisfied.

The Retrieval Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) is based on the design presented in the SCP repository conceptual design report (KE/PB, 1987b) and on current design assumptions that include (1) a waste container design of heavy-walled carbon steel surrounded by packing material of crushed basalt and bentonite clay both enclosed by a low-carbon steel outer shell, and (2) the waste package emplaced in a short horizontal borehole configuration in the Cohasset basalt flow 3,000 ft below the Hanford Site in Washington State.

A complete description of the surface and subsurface repository design is presented in Chapter 6.0 of this document. In accordance with the DOE position on retrievability and retrieval, retrieval concepts, methods, and

nonstandard equipment necessary for retrieval shall be (1) designed and engineered, before license application, so that the retrieval method will successfully operate and function under a range of adverse underground conditions; (2) designed and fabricated for mock-up tests during a proof-of-principle demonstration period before the license application; and (3) further developed and tested, if needed, under selected repository conditions during the review of the license application and repository construction during performance confirmation.

Link to Performance Issue 2.4

Section 8.2 of the SCP uses the issue resolution strategy to establish what data are needed to design and license a nuclear waste repository in basalt. The goal of the issue resolution strategy is to develop a list of measurable parameters that were derived from regulatory requirements. From these regulatory requirements a series of performance measure goals were selected and, by the use of analytical tools, directly measured parameters were defined. Section 8.3.2.6 explains how a repository design that allows for retrieval will be developed. The testing program for the site characterization data that this design is sensitive to will ultimately be used to resolve issues under Key Issue 2 in SCP Section 8.2.2. The linkage of this Section 8.3.2.6 to the issue resolution strategy is through Key Issue 2 and performance Issue 2.4 listed below:

Key Issue 2--"Will the projected releases of radioactive materials to restricted and unrestricted areas and the resulting radiation exposures of the general public and workers during repository operation, closure, and decommissioning at the Hanford Site, meet applicable safety requirements set forth in 10 CFR 20, 10 CFR 60, 10 CFR 960, and 40 CFR 191?" (DOE, 1987c)

Key Issue 2 is further divided into issues specific to performance, and design. The one performance issue dealing with retrievability follows:

Performance Issue 2.4--"Can the repository be designed, constructed, operated, closed, and decommissioned so that the option of retrieval will be preserved as required by 10 CFR 60.111?" (DOE, 1987c)

Summary of program

Federal regulations 10 CFR 60.111(b) and 10 CFR 60.133(c) (NRC, 1987a) require that the option of retrieving any or all spent fuel and other high-level radioactive waste emplaced in a geologic repository must be preserved. The retrievability period extends from the time of initial waste emplacement until regulatory permission is granted to terminate the option (specified to be up to 50 yr for planning purposes). Design consideration of retrievability strategies is necessary to ensure that waste retrieval is feasible using reasonably available technology and that the repository design is compatible with the requirement to preserve the retrievability option. Therefore, waste retrieval is treated as a specific preclosure performance requirement and design category within the repository program. Design consideration of waste retrieval strategies is needed as part of site characterization planning to

determine whether additional site characterization data are needed and to ensure compatibility between waste retrieval testing needs and planned site characterization testing activities.

The following two activities are discussed in Section 8.3.2.6 in regard to waste retrieval:

- Compilation of retrievability strategy report.
- Development and demonstration of retrievability equipment.

The first activity discusses the different normal and abnormal retrieval scenarios during operations. The second activity discusses the proof of principle testing deemed necessary to demonstrate that planned retrieval methods and equipment will perform properly under adverse operation conditions.

8.3.2.6.1 Purpose and objectives

The purposes of the waste retrieval investigation and supporting activities are to define the waste retrieval strategies to be incorporated into the waste package and repository designs and to identify the necessary equipment development and demonstration testing for compliance with the DOE position on retrievability and retrieval. A near-term objective is to ensure that waste retrieval data needs and testing requirements are integrated with other facets of the site characterization program. In addition, Section 8.3.2.6 justifies the parameter needs by linking them to the issue resolution strategy of Issue 2.4.

The Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) provides a project position for compliance with the DOE position on retrievability and retrieval. In addition, the Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) presents the strategy to meet the requirements such as the Nuclear Waste Policy Act of 1982 (NWP, 1983) and both 10 CFR 60.111(b) and 10 CFR 60.133(c).

A series of objectives have been established. The first objective is to identify the various retrieval scenarios that have been postulated for the nuclear waste repository in basalt. The worst-case environmental conditions, the conditions of the geologic setting, and the condition of the engineered structures and waste package are then established for those scenarios. The second objective is to identify the proof-of-principle testing program to demonstrate that the option to retrieve will be maintained regardless of the conditions postulated.

To accomplish the retrievability regulatory requirements, the Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) identified the following considerations:

- Maintaining the retrievability of each waste container for the prescribed retrieval period.
- Ensuring that designs, methods, and equipment used do not negatively affect isolation.
- Maintaining retrievability throughout the range of underground conditions that could be caused by any singular or combination of plausible events.
- Anticipating the range of thermal, hydrological, mechanical, and chemical conditions occurring throughout the retrieval period.
- Estimating the time and labor required to provide temporary storage of waste being retrieved.
- Determining the plans for the necessary demonstrations of methods, equipment, operation, and procedures.
- Early backfilling of pre-designated portions of the repository if required.
- Implementing appropriate and necessary monitoring.

The basic design assumption is that the equipment, systems, and procedures required for retrieval from the nuclear waste repository in basalt will not have been constructed, installed, and maintained in a constant state of readiness awaiting an order for retrieval. Rather, the methods, plans, and contingencies for retrieval will be designed, tested, and made ready for implementation if and when they are required.

8.3.2.6.2 Rationale

The rationale for the waste retrieval investigation recognizes that confidence in waste retrieval capability can only be achieved by incorporating a retrieval strategy as a planned contingency in the mined geologic disposal system design and by performing demonstration tests to show that the retrieval strategy can be successfully implemented under all credible conditions. Project-specific waste retrieval strategies are needed to implement the generic DOE position on retrievability and retrieval caused by inherent differences in geologic media and their associated emplacement designs.

The mined geologic disposal system in basalt will be designed to satisfy the DOE position on retrievability and retrieval. Since waste package designs, emplacement concepts, and normal and adverse underground conditions

vary among the candidate sites, the associated retrieval concepts, methods, and equipment requiring testing are site-specific. The Retrieval Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) ensures compliance with the generic DOE position on retrievability and retrieval for a site-specific design. This report is being prepared concurrently with, and in support of, the SCP to ensure compatibility with waste package and repository design development.

8.3.2.6.3 Description of activities

The following two engineering activities describe the waste retrieval strategies to be incorporated into the waste package and repository designs and identify the necessary equipment development and demonstration testing required for compliance with the DOE position on retrievability and retrieval (DOE, 1986a).

8.3.2.6.3.1 Compilation of retrievability strategy report

The Retrieval Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) describes how the BWIP intends to conform to the DOE position on retrievability and retrieval for a geologic repository. The following specific tasks are included in the BWIP retrievability strategy:

- Identify through predictive modeling the geomechanical, thermal, hydrological, and chemical conditions that could exist in the repository during the period when retrievability may be required.
- Identify the different retrieval scenarios that are postulated as being credible under normal and abnormal events/conditions.
- Describe the repository design, waste package, and waste emplacement configuration, and alternatives for waste emplacement that may be considered.
- Identify the type and number of proof-of-principle demonstration tests recommended to satisfy the DOE position on retrievability and retrieval.
- Identify and describe the equipment and instrumentation required to perform the proof-of-principle demonstration tests.
- Identify where the demonstration tests are to be conducted.
- Identify requirements for evaluating and assessing risks associated with retrievability.

- Identify future work required to support retrievability, including the detailed design and development of facilities, equipment, instrumentation, and any other prototypic demonstrations that may be required to fully support the BWIP retrievability strategy.

Retrievability of waste under both "normal" and "abnormal" conditions in the nuclear waste repository in basalt is required. The normal and abnormal condition strategies shall include any or all of the emplaced spent fuel and high-level waste in the nuclear waste repository in basalt up to the time the retrieval decision is made. The repository environment and geotechnical conditions for "normal and abnormal conditions" assume that the shafts, hoists, and all underground electrical and mechanical equipment have been maintained and are capable of being brought back into service within a reasonable schedule. Abnormal conditions may require specialized equipment to be fabricated and may require a longer time to become operational.

The retrieval of waste from the nuclear waste repository in basalt can start anytime over a 50-yr period beginning at the time of emplacement. During this time period the condition of the waste package may degrade and the environment that surrounds the waste package may change. The impact of the change may plausibly result in retrieval conditions that range from normal to abnormal. Retrieval must be assured for the range of conditions defined in the following sections.

8.3.2.6.3.1.1 Normal.

It is assumed, for the worst-case normal condition, that by the time the waste is retrieved, the waste package shell has deteriorated to the point that moisture in the form of water and steam has caused the packing material to swell and thus to apply a compression load on the waste container shell. Therefore, normal retrieval will be based on the premise that the waste container is firmly embedded within the packing material and the emplacement borehole.

8.3.2.6.3.1.2 Abnormal.

Four bounding abnormal scenarios will be developed. These scenarios include the assumptions of a collapsed borehole, a flooded repository, a breached container, and a collapsed emplacement room.

1. The collapsed borehole retrieval scenario considers the effects on retrievability if the emplacement borehole collapses over its entire length. The scenario assumes that either the waste package shell is intact or that the waste package shell has deteriorated as in the case of normal retrieval. Rock loads are imposed on the waste container in addition to the loads imposed by swelling of the packing material.
2. The flooded repository scenario considers the effects of flooding on retrievability. The major effect of the flooding will be on the waste package packing material, although the total repository

environment will be impacted. The scenario will assume that the total repository underground has been inundated with water and saturated steam vapor and that it will require five years to pump out the repository and reestablish the services and be ready for access. During this flooded period it is assumed that the packing material around the waste containers has been saturated and no longer provides a stable support or surrounding for the waste container, allowing the container to settle in the borehole. Definition of the ventilation required to remove the moisture from the repository environment will be a major factor in this scenario.

3. A breached container scenario is the most significant of the abnormal scenarios. It assumes that the heavy-walled container has failed and that radionuclides (gases and solids) have leached from the waste form and migrated into the surrounding packing material and the host rock surrounding the emplacement borehole. In addition, a retrieval-caused breached container scenario is being considered.
4. The collapsed emplacement room scenario considers the effects on retrievability if the roof of an emplacement room collapses. Roof support is designed to maintain stability through the retrieval period. Spalling will be addressed as general cleanup and is considered as a maintenance activity. If this scenario did happen, it would pose no new problems as mining through caved ground is not that unusual, and therefore proof-of-principle testing will not be performed. Additional related information on opening stability is discussed in Chapters 2 and 6 in Section 8.2.2 (Issue 2.4 and 2.7) and in Section 8.3.2.2.3.4.

The specific means by which retrieval will be accomplished shall be defined in the Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) and in the License Application Design. The development of a strategy for retrieval that is based on the selection of a single worst-case parameter occurring at a single point in time will not provide adequate assurance because the actual retrieval time may occur when a different worst-case parameter is controlling. Therefore, it is intended to use the worst-case for each parameter regardless of when that worst-case would occur during the retrieval time period. The purpose of this approach is to bound the retrieval conditions and demonstrate that waste can be retrieved at any time from the start of the retrievability period until the end of actual retrieval.

Scenarios that include the worst-case parameters will be evaluated and a system design will be developed that will retrieve waste from all parts of the repository under the scenario conditions.

The repository conditions likely to exist at the time of retrieval depend on the duration that the waste has been emplaced. Retrieval can start anytime over a 50-yr period beginning at the time of emplacement. Conditions during actual retrieval could vary significantly with time and location. Two conditions that may vary with location are temperature and groundwater volume.

The waste retrieval process is sensitive to the information and data from site characterization activities identified in Tables 8.2.2.2.4-1 and 8.2.2.2.4-2 in Section 8.2.2.2.4 and applicable sections referenced therein. This listing of parameters, derived from performance measures and analytical tools in Section 8.2.2.2.4, is the most inclusive for supporting preclosure performance requirements. The parameter groups include site rock mass properties and hydrologic, geologic, geophysical, and configuration parameters. The data from these tables will be used to fulfill three major functions of Issue 2.4:

- Maintain access to and from emplaced waste.
- Provide retrieval of waste container from emplacement borehole.
- Transport waste container to surface.

Analysis methods for underground opening stability under the influence of the thermal load are adequate for conceptual design. However, these methods are not well supported, and further development and additional data acquisition will be required during the site characterization and license application design phases.

It will be necessary to develop improved methods of analysis for design and performance prediction of underground openings. These methods should be based on measurable rock parameters, adjusted by test results from the Exploratory Shaft Facility and monitoring observations, capable of validation by performance observations, and useful for the establishment and implementation of the performance confirmation program.

Additional data requirements include improvement of the data base for the following parameters:

- Rock mass strength formulation.
- In situ stress.
- Deformation modulus of rock mass.
- Thermal expansion coefficient.

Sensitivity studies of parameters have been conducted on several of these parameters and are listed in the SCP repository conceptual design report (KE/PB, 1987b).

While the design of stable openings will limit the amount and effect of any postulated rock bursting, induced fracturing, and caving, the method of determination for their potential at the present time is based on case histories and empirically derived relationships. Further theoretical analysis and continuous field monitoring are required within all the underground facilities.

8.3.2.6.3.2 Development and demonstration of retrieval equipment

This activity consists of the equipment development and demonstration activities identified in the Retrieval Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c). The primary emphasis in this activity is on the proof-of-principle testing deemed necessary to demonstrate that planned retrieval methods and unique equipment items will perform as required under normal and credible abnormal conditions. This proof-of-principle testing is considered to be required to support the repository license application now and beyond the time of licensing.

Demonstration testing will be conducted in repository simulated environments in order to test the particular design or operating features. Some tests that relate primarily to equipment check-out can be performed in surface-test facilities rather than in an excavated opening. Testing that requires an excavated basalt environment, but not necessarily the actual repository location, can be simulated in the Near-Surface Test Facility. However, there will be some proof-of-principle testing that can credibly be performed only in the actual repository host rock; such tests would logically be performed in the Exploratory Shaft Facility being constructed early in the site characterization phase. Actual proof-of-principle test planning is not yet completed, and its potential interfaces with the current exploratory shaft design and other planned tests have not been evaluated yet.

The proof-of-principle testing will demonstrate normal and abnormal retrieval according to the scenarios previously described.

Four proof-of-principle tests are currently planned for BWIP to demonstrate retrievability:

- Normal retrieval scenario.
- Collapsed borehole scenario.
- Flooded repository scenario.
- Breached container scenario.

Normal condition proof-of-principle testing will evaluate those features of the retrieval system that are critical to the removal of the waste container from a waste package with wet packing. The proof-of-principle testing shall evaluate (1) those equipment features that must apply retrieval loads to the container without damaging the container and (2) the equipment and techniques that are to be used to remove or retain the wet packing material within the emplacement borehole.

Abnormal condition proof-of-principle testing will evaluate those features of the retrieval system critical to the removal of the waste container from the waste package under (1) a collapsed borehole scenario, (2) a flooded repository scenario, and (3) breached container scenarios.

The proof-of-principle testing will evaluate the following equipment features:

- That remove or retain wet packing within the emplacement borehole.
- That determine the condition of the container before it is removed from the emplacement borehole.
- That remove host rock from around the container without damaging (or further damaging) the container.
- That contain or minimize the release of radioactive material from the container during retrieval handling.
- That prevent the release of radioactive material when transporting contaminated host rock, contaminated packing, or waste containers to the surface.
- That allow remote operated man-in-the-loop retrieval of waste containers, packing, or host rock, under those scenarios where the conditions in the emplacement room will not permit entry by repository workers.

The Retrieval Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) provides details of the proof-of-principle demonstration tests and the locations where they will be performed. These proof-of-principle retrievability demonstrations have been identified primarily to provide the confidence necessary for the BWIP to satisfy the DOE position on retrievability and retrieval and other regulatory requirements.

Additional information and data will be required during site characterization to provide verification of geomechanical, hydrologic, and geothermal conditions that have been assumed. The waste retrieval process has been determined sensitive to the information and data from site characterization activities identified in Tables 8.2.2.2.4-1 and 8.2.2.2.4-2 of Section 8.2.2.2.4. This listing of parameters, derived from performance measures and analytical tools in Section 8.2.2.2.4, is the most inclusive for supporting preclosure performance requirements. The parameter values obtained through site characterization activities will be used to design retrieval tests as nearly identical to in situ conditions as practicable to assure yielding the most useful results possible.

8.3.2.6.4 Applications of results

The results of these activities within the waste retrieval investigation will be used to show design compliance with all federal laws, regulations, and standards that pertain to waste retrievability and waste retrieval operations.

Such compliance will be based upon the generic guidance provided by the DOE position on retrievability and retrieval (DOE, 1985a). These results will be particularly pertinent in preparing the repository license application.

8.3.2.6.5 Schedules and milestones

The Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c) is currently in progress. This initial report will cover only retrieval under normal conditions and will be based only upon the current reference emplacement concept. The activity will continue subsequent to this initial report to include retrieval under abnormal conditions and to include evaluation of selected alternative emplacement concepts from a retrievability standpoint. This further work will be completed during an early portion of advanced conceptual design phase, and will be a basis for determining the need for and timing of future activity iterations.

More detailed planning for the retrieval equipment development and demonstrations will be conducted early based on recommendations presented in the Retrievability Strategy Report for the Basalt Waste Isolation Project (KE/PB, 1987c). The schedule for this proof-of-principle testing is shown in Figure 8.3.2.6-1. Actual testing is planned to extend at least until the time of repository license application.

8.3.2.6-13

ACTIVITY	TIME									
WASTE RETRIEVAL		▽ ¹	▽ ²	▽ ³						

PSDR-2016-8.3.2.4

THE CURRENT LOGICS DIAGRAM FOR RETRIEVABILITY REQUIRES DESIGN OF PROOF OF PRINCIPLE TESTING FOR PHASES 1, 2, AND 3. THIS TESTING WILL START AS SHOWN AND CONTINUES AT LEAST TO THE START OF LICENSE APPLICATION DESIGN. PHASE 1 TESTING HAS BEEN PROPOSED TO BE COMPLETED AT THE HIGH BAY FACILITY AT 337 BUILDING, PHASE 2 AT THE NEAR-SURFACE TEST FACILITY, AND PHASE 3 AT THE EXPLORATORY SHAFT. PHASE 3 WILL BE COMPLETED IF REQUIRED AS A RESULT OF TESTING DURING PHASES 1 AND 2.

- ▽¹ PHASE 1
- ▽² PHASE 2.
- ▽³ PHASE 3.

Figure 8.3.2.6-1. Schedule for waste retrieval proof-of-principle testing.

This page intentionally left blank.

9 2 1 2 5 5 5 0 5 2 6

8.3.2.7 Specific design program for radiological health and safety

The mined geologic disposal system in basalt will be designed per the requirements of 10 CFR 60 (NRC, 1987a) to limit the expected radiation doses to workers and the public during construction, operation, and closure of the repository to less than the allowable limits required by 10 CFR 20 (NRC, 1987b) and 40 CFR 191 (EPA, 1986). The three investigations defined within this section address the design of the repository considering normal operating conditions and accident scenarios and their impact on radiological health and safety of workers and the public.

Background

The presence of radioactive waste material will pose specific health and safety concerns for the workers and the public at the mined geologic disposal system in basalt. The NRC has used 10 CFR 60.131(a) (NRC, 1987a) to invoke protection against radiation hazards cited in 10 CFR 20 (NRC, 1987b), which applies to all activities under licenses issued by the NRC. In addition to complying with the requirements set forth in 10 CFR 20, every reasonable effort will be made to maintain radiation exposures as low as reasonably achievable. The term "as low as reasonably achievable" (ALARA) means as low as reasonably achievable considering the state of technology and the economics of improvements in relation to the benefits to the public health and safety and other societal and socioeconomic considerations. Exposure will be kept as far below regulation limits as feasible. Design guidelines are established at a fraction of the limits to ensure that necessary operations can be performed and occupational dose maintained below allowable limits.

In addition to the concerns for worker health and safety, 10 CFR 60 addresses public health and safety concerns. Design guidelines are established to ensure that the radiological dose to the public is maintained below allowable limits. The repository design will provide a framework for assessing the radiological risk to the public from operation of the repository. The methods to be used in conducting these safety assessments will be developed by the Preclosure Risk Assessment Methodology (PRAM) program. This program is described in Section 8.3.5.1.

Link to Issues

Section 8.2 uses the issue resolution strategy to establish what data are needed to design and license a nuclear waste repository in basalt. The goal of issue resolution strategy is to develop a list of measurable parameters that are derived from regulatory requirements. From these regulatory requirements a series of performance measure goals are selected and, by the use of analytical tools, directly measured parameters are defined. Section 8.3.2.7 describes how a repository design will be developed that protects the radiological health and safety of the workers and public. The testing program for the site characterization data that this design is sensitive to will ultimately be used to resolve issues under Key Issue 2 in Section 8.2.2.

This section is linked to the issue resolution strategy (DOE, 1987c) through Key Issue 2 and the specific issues listed below:

Key Issue 2--"Will the projected releases of radioactive materials to restricted and unrestricted areas and the resulting radiation exposures of the general public and workers during repository operation, closure and decommissioning at the Hanford Site, meet applicable safety requirements set forth in 10 CFR 20, 10 CFR 60, 10 CFR 960 and 40 CFR 191?" (DOE, 1987c)

Key Issue 2 is further divided into issues specific to performance and design. Four performance issues and one design issue deal either directly or indirectly with the radiological health and safety of workers and the public. These issues are as follows:

Performance Issue 2.1--"During repository operation, closure, and decommissioning (a) will the expected average radiation dose received by members of the public within any highly populated area be less than a small fraction of the allowable limits and (b) will the expected radiation dose received by any member of the public in an unrestricted area be less than the allowable limits as required by 10 CFR 60.111, 40 CFR 191 Part A, and 10 CFR 20?" (DOE, 1987c)

Performance Issue 2.2--"Can the repository be designed, constructed, operated, closed and decommissioned in a manner that ensures the radiological safety of workers under normal operations as required by 10 CFR 60.111 and 10 CFR 20?" (DOE, 1987c)

Performance Issue 2.3--"Can the repository be designed, constructed, operated, closed and decommissioned in such a way that credible accidents do not result in projected radiological exposures of the general public at the nearest boundary of the unrestricted area, or workers in the restricted area, in excess of applicable limiting values?" (DOE, 1987c)

Performance Issue 2.4--"Can the repository be designed, constructed, operated, closed, and decommissioned so that the option of retrieval will be preserved as required by 10 CFR 60.111?" (DOE, 1987c)

Design Issue 2.7--"Have the characteristics and configurations of the repository been adequately established to (a) show compliance with the preclosure design criteria of 10 CFR 60.130 and 133 and (b) provide information for the resolution of the performance issues?" (DOE, 1987c)

Summary of program

This program consists of three investigations to address the design of the repository and the impact on the worker radiation safety and health.

Section 8.3.2.7.3 describes the investigation needed to apply existing methodology to predict the radiation doses that will be received by the repository personnel during normal operations. Issues 2.2, 2.4, and 2.7 relate to this section.

Section 8.3.2.7.4 defines the investigation needed to determine methods necessary to recover from accident conditions postulated by the Preclosure Risk Assessment Methodology. Issue 2.3 relates to this section.

Section 8.3.2.7.5 describes the investigation needed to identify necessary radiation monitoring systems for repository operations during all phases of operation and under both normal and accident conditions. Issues 2.1, 2.2, 2.3, 2.4, and 2.7 relate to this section.

For each of the investigations, the primary input will be the design and (or) design subactivities of either the advanced conceptual design or license application design. A much smaller portion of the input for these investigations will come from site characterization data gathering activities.

8.3.2.7.1 Purpose and objectives

The purpose of this section is to define the investigation and engineering studies necessary to assure that the repository can be designed, constructed, and subsequently operated in a manner that provides for the radiological health and safety of workers and the public. In addition, these sections will identify the design-related parameter needs by linking them to the issue resolution strategies of 2.1, 2.2, 2.3, 2.4, and 2.7.

8.3.2.7.2 Rationale

To ensure compliance with the 10 CFR 20 (NRC, 1987b) requirements, the expected doses to the workers will be quantified. This quantification of radiation doses will be performed by applying accepted analytical models to the successive repository designs (i.e., advanced conceptual design and license application design). Additionally, the design will provide for monitoring systems that will measure the dose actually received by the repository workers and (or) released to the public.

Input to the worker and public radiation exposure models will consist of design features and site characterization data. As the design matures and the appropriate design features become better defined, the accuracy of the models will increase. The design will define the facilities, processes, and activities necessary for repository construction and operation. The number of workers necessary for each activity and the duration and frequency of each task must be known to calculate the doses to each worker. The layout and physical design will also be input into the model by defining the materials

used as shielding and their thicknesses. It will also identify personnel-occupied areas, source locations and storage areas, and transport and personnel corridors. The throughput of radioactive materials and the specific source terms of all forms of radiation will be identified.

The gathering and input of site-specific data or information also will result in an increase in model accuracy. Data on the following characteristics of the site will be needed for input into models to accurately calculate radiation doses to the workers and (or) the public:

- Natural radioactive materials in the basalt and their diffusion rate into air.
- Radiation attenuation properties of the basalt.
- Meteorological conditions that will disperse radionuclides.

In addition to the prediction of doses to workers and the public, the design of the repository will need to include performance verifications systems that will monitor radiation levels and alarm if an unacceptable variation from normal levels occurs. Other controls that need to be incorporated into the administration program include provisions of dosimeters worn by personnel so that the actual dose received by each repository worker can be determined.

The following three investigations defined within this section address the design of the repository and impact on worker radiation safety and health. Also listed are the issues relating to each investigation.

- Normal operational radiological protection - (Issues 2.2, 2.4, 2.7).
- Accident conditions for radiological protection - (Issue 2.3).
- Radiological monitoring systems - (Issues 2.1, 2.2, 2.3, 2.4, 2.7).

8.3.2.7.3 Investigation of normal operational radiological protection

Issues 2.1, 2.2, 2.4, and 2.7 relate to this investigation will apply the Preclosure Risk Assessment Methodology program to predict the radiation doses that will be received by the repository personnel and the public during all phases of construction and operation. Doses due to radon and sources due to testing will be measured prior to and during waste emplacement.

8.3.2.7.3.1 Purpose and objectives

The purpose of this investigation is to apply the methods developed by the Preclosure Risk Assessment Methodology program to predict the radiation doses that will be received by the repository personnel and public and to show that the doses will be less than the allowable limits. Computer models will

be used to evaluate the facility design and operating scenarios for radiation doses. The information obtained from this analysis will allow for the exact quantification of radiologic doses received. After evaluation of the data, it may be determined that design changes are required or administrative controls may be established that would serve to maintain dose levels below the regulatory limits.

8.3.2.7.3.2 Rationale

This investigation is necessary to determine the radiation doses that are received under normal operating conditions that are limited by 10 CFR 20 (NRC, 1987b). Specifically, the following are the radiation exposure limits, taken from NRC (1985) and calculated on a rems-per-calender-quarter basis:

1. Whole body; head and trunk; active blood forming organs; lens of eyes; or gonads 1.25
 2. Head and forearms; feet and ankles 18.75
 3. Skin of whole body 7.5
- (b) A licensee may permit an individual in a restricted area to receive a total occupational dose to the whole body greater than that permitted under paragraph (a) of this section provided:
- (1) During any calendar quarter the total occupational dose to the whole body shall not exceed 3 rems; and
 - (2) The dose to the whole body, when added to the accumulated occupational dose to the whole, shall not exceed 5 (N-18) rems where N equals the individual's age in years at his last birthday.

8.3.2.7.3.3 Description of activities

The required information will be produced as part of the advanced conceptual design and (or) license application design as specified by the Mission Plan (DOE, 1985b). The advanced conceptual design and license application design efforts will consist of a great many subtasks or activities that range from the purely conceptual to the strictly analytical. The result of some of these activities, such as the radiation field plot model, will provide direct input for resolving issues; other activities will provide the raw material from which to perform further design and analysis, like the facility design description for use by the Preclosure Risk Assessment Methodology program. The following are subtasks within the effort to provide advanced conceptual and license application designs.

8.3.2.7.3.3.1 Evaluation of the application of robotics.

The principles and philosophy of ALARA are based on the assumption that any exposure of personnel to ionizing radiation is to be avoided if practicable. Automated robotic design of waste handling equipment is the best alternative to achieving the condition ALARA. Using robots for inspection of the closed-off emplacement rooms to minimize worker exposure is also a consideration. The evaluation criteria development and tradeoff study models for this study are currently being developed by Westinghouse Hanford Company.

Remote maintenance and repair of the hot cell processing equipment using dedicated robotics must be considered because the hot cell will be an area of high radiation exposure. The consideration of maintenance extends to the design of the facility structure and support systems as well as the equipment. For example, decontamination systems, air locks, and hot shops must be provided to repair the automated processing hardware.

Design of waste packaging, rod consolidation, and retrieval equipment will form the major portions of this activity. Prototypic consolidation equipment is being designed and built at the Idaho National Engineering Laboratory. These efforts will provide a large input to this task. Waste packaging, closure welding, nondestructive examination techniques and other applications, are being developed and will be discussed in the waste package documentation.

Equipment to load the waste container onto the hoist and again unload the waste at the bottom of the shaft is a candidate for robotic application.

Retrieval is an activity that will require considerable new and unique applications of remote handling technology. A demonstration is needed to show that remote retrieval is possible to safely remove waste from an emplacement room that may be highly contaminated due to several breached waste packages.

The following are activity inputs that will be used for the robotics remote handling demonstration:

- Model, radiation.
- Model, waste processing flow.
- Waste package engineering plan.
- Rod consolidation study.
- U.S. Department of Energy development activities.
- Westinghouse Hanford Company robotics application study.

8.2.3.7.3.3.2 Evaluation of ionizing radiation fields.

A detailed assessment of repository radiation fields will be performed. This study is necessary to fulfill the requirement imposed on the BWIP of ALARA that assures worker exposure does not exceed established limits. The analysis is to be based on the design and operational description of the

repository that includes the transfer cask, waste package, and host rock as defined by the designs. This work should be done as part of the license application design effort and issued either as a "stand alone" document or an appendix. The design inputs are the design descriptions from the advanced conceptual design and the license application design.

8.3.2.7.3.3.3 Waste processing flow model.

The waste processing flow model will describe the movement and in-process storage of the waste from the time it is received at the repository until final underground emplacement. The primary inputs to the waste processing flow model are as follows:

- Waste form receipt sequence (i.e., burnup, age, type, defense).
- Waste package(s) payload, both in tons and watts.
- Underground thermal limits and need to "level" waste package wattage.
- Container closure time data from waste package design and development plans.
- In-Process storage capacity.
- Packaging rate (e.g., number of parallel process streams, etc.).
- Underground transport and emplacement rates.
- Equipment downtime and routine maintenance requirements.
- Hoisting capacity.
- Staffing levels and number of shifts worked per day.

The Mission Plan (DOE, 1985b) requires the basalt repository to process 3,000 MTU spent fuel and 400 MTU defense waste per year; all of the model inputs listed above impact meeting this goal. The primary purpose of this model is to enable the waste handling subsystem designers to quantify the internal model inputs in terms of both cost and capacity and study the system's response to changes in external model inputs.

The waste processing flow model will receive information from the following studies and tests:

- Waste package assembly location study.
- Robotic application study.
- Interruptions in waste processing study.
- Emplacement cycle time testing.
- Retrieval cycle time testing.
- Underground transporter testing.

- Hot cell equipment cycle testing.
- Rod consolidation equipment testing.
- Container loading testing.
- Off-normal event recovery equipment testing.

8.3.2.7.3.3.4 Radiation shielding/exposure model.

The radiation shielding/exposure model will be used to analyze and predict operating personnel exposure intensity levels to ionizing radiation and integrated occupational doses. In addition, it will calculate exposure limit worker radiation doses. This model will be used to demonstrate ALARA compliance and, by necessity, must follow advanced conceptual design facility and equipment detailing. Radiation field intensities will be calculated from the design presented in the advanced conceptual design effort.

The following sources of information will be needed to develop the radiation shielding/exposure model:

- Operator exposure to radiation.
- Waste processing flow model.
- Characteristics of spent fuel from the waste forms investigation.

8.3.2.7.3.3.5 Criticality model.

The criticality model will be used to analyze maximum batch limit sizes for the various storage sites within the repository. This analysis will be based on the spent-fuel character and the geometric designs (as per advanced conceptual design) of the storage site. Models to do this type analysis are commercially available and will not require development. The criticality model will need input from the following:

- In-process waste storage study.
- Characteristics of spent fuel from the waste package engineering plan.

8.3.2.7.3.3.6 Evaluation of retrieval methods.

An interface exists between this section and Section 8.3.2.6, waste retrieval. The waste retrieval process in Section 8.3.2.6 will need to be evaluated to ensure that the doses received do not exceed the regulatory limits. The following inputs are needed for the retrieval method evaluation:

- Model, radiation.
- Waste container retrieval force testing.

8.3.2.7.3.3.7 Ventilation, filtration, and leakage model.

Ventilation, filtration, and leakage models will provide characterization of airborne radioactive releases. The effectiveness of the filtering system and the impacts of isolating the ventilation system through the repository surface and subsurface facilities to the controlled process area environment will be determined by the model. These models will also provide input information for contamination prevention, monitoring systems, dispersion models of radioactive effluent, and the location of release. Dispersion models will be used to quantify the occupational and public dose from airborne effluent releases (e.g., top of the stack, basalt pile) within the central process area but outside the surface facilities.

The ventilation, filtration, and leakage model design is sensitive to the following site characterization data identified in the issue resolution process (DOE, 1987b). This investigation requires the following data to be provided by the site characterization activities:

- Host rock shielding characteristics, identified by Issues 2.1, 2.2, and 2.7; the tests to obtain these data are described in Section 8.3.1.2--Geology.
- Radon evolution from the host rock, identified by Issues 2.1, 2.2, and 2.7; the tests to obtain these data are described in Section 8.3.1.2--Geology.
- Natural phenomena (wind, rain, etc.), identified by Issues 2.1, 2.2, and 2.7; the tests to obtain or confirm these data are described in SCP Section 8.3.1.5--Climatology.

8.3.2.7.3.4 Application of results

The results of this investigation will be used in supporting the design, performance, and safety analysis of the repository, in particular the advanced conceptual design and license application design. In addition, this investigation will provide input for the safety analysis report and environmental impact statement.

Specific applications of the investigation results from the following underlined activities are listed below:

A. Evaluation of the application of robotics

- Advanced conceptual design and license application designs efforts must use these data in calculating cost/benefit of robotic application as it applies to an ALARA analysis.
- This data will be used for the resolution of Issues 2.2 and 2.7.

B. Evaluation of the ionizing radiation fields

- This evaluation will form the data base of radiation field intensities on which worker exposure will be calculated for 10 CFR 20 (NRC, 1987b) compliance. This study will provide the rate part of the calculation(s), and the waste processing flow model will give the time data for the calculation.
- The data based formed from this study will be used for the resolution of Issues 2.1, 2.2, and 2.7.

C. Waste processing flow model

- This model will define quantitatively the movements of source terms (e.g., spent fuel) throughout the repository facility. This will include lag and surge storage inventories and transport times through tunnels, drifts, and shafts. It will also include emplacement and retrieval times adjacent to the borehole. When the time durations generated by this model are coupled with the rate data from the field intensity evaluation, a clear picture of design deficiencies and (or) personnel management will develop. The application of this model should occur many times during the iterative design phases.
- This model will be used in the resolution of Issue 2.2.

D. Radiation shielding/exposure model

- When the time durations generated by the model described in "C" above are coupled with the rate data from the field intensity study in "B" above, a clear picture of deficiencies in design and (or) personnel management will develop. The application of this model should occur many times during the iterative design phases.
- This model will be used in the resolution of Issues 2.1, 2.2, 2.4, and 2.7.

E. Criticality model

- This model will be used to design/analyze various storage or holding areas within the repository to preclude a criticality incident. Prevention of criticality is essential to the radiation exposure protection of the workers.

F. Evaluation of retrieval methods

- (Refer to Section 8.3.2.6 on waste retrieval.)

G. Ventilation, filtration, and leakage model

- This model will help determine the risk of contamination and identify the needs and locations for appropriate monitoring devices. Significant deficiencies in the control of contamination that are identified by this model will trigger a design modification to remedy the defect.

8.3.2.7.3.5 Schedule and milestones

Preliminary data may exist for some of the activities. This information must be reviewed for adequacy to determine whether additional testing is required. Some of the required testing will be accomplished in the Exploratory Shaft Facility. The design schedule is defined in other documents. Advanced conceptual design will be the next major phase.

8.3.2.7.4 Investigation of accident conditions for radiological protection

Issue 2.3 relates to the investigation of accident conditions for radiological protection, which identifies and analyzes the methods necessary to recover from accident conditions. These methods will be developed by the Preclosure Risk Assessment Methodology program and are described in Section 8.3.5.1.

8.3.2.7.4.1 Purpose and objectives

The purpose of the investigation of accident conditions for radiological protection is to identify and analyze the methods necessary to recover from the accident conditions. The objective of preclosure analysis is to minimize worker and public radiation exposure and contamination during an accident and during the recovery effort from these accident conditions.

8.3.2.7.4.2 Rationale

The mined geological disposal system in basalt will be designed per the direction of 10 CFR 60 (NRC, 1987a) to limit the expected radiation doses during construction, operation, and closure of the repository.

8.3.2.7.4.3 Description of activities

The required information will be produced as part of the advanced conceptual design and (or) license application design. These two design efforts are iterative processes where a design solution is proposed, analyzed, and the results of the analysis factored back into the design. One such analysis is the Q-list, which is oriented toward identifying scenarios of failure that would result in a radiation dose to the public in excess of regulatory limits. This study will consider the same events from the viewpoint of radiation dose to the worker. An example Q-list scenario would

be a cask dropped down the shaft with a subsequent radionuclides release from the waste package. A planned means to mitigate the consequences to the public from this event would be the exhaust air filtration system. The corollary to this scenario for worker radiation protection would be to design this filter system for remote filter replacement, thereby minimizing or eliminating risk of exposure or contamination.

This activity will use the Preclosure Risk Analysis Methodology report and Q-list results as input and perform further analysis from the standpoint of limiting occupational doses.

The design is sensitive to the following site characterization data identified in the issue resolution process. The investigation of accident conditions for radiological protection requires the following data to be provided by site characterization activities:

- Radionuclide/material removal character of pathways, identified by Issue 2.3; the testing to obtain this data is described in Section 8.3.1.4--Geochemistry.
- Wind speed and direction, identified by Issues 2.3 and 2.7; the testing to obtain or confirm this data is described in Section 8.3.1.5--Climatology.
- Precipitation, identified by Issues 2.3 and 2.7; the testing to obtain or confirm this data is described in Section 8.3.1.5--Climatology.
- Host rock shielding, identified by Issue 2.7; the testing to obtain this data is described in Section 8.3.1.2--Geology.
- Friction factor of airway lining is identified by Issue 2.4.

8.3.2.7.4.4 Application of results

The results of this investigation will be used to support the design and performance analysis of the repository, in particular the advanced conceptual design and license application design. In addition, this investigation will provide input for the safety analysis report and environmental impact statement.

8.3.2.7.4.5 Schedule and milestones

The requirements search is currently being performed and will be issued in the requirements documents. The design schedule is defined in other documents; the advanced conceptual design is the next major design phase. Some of the data needs for shielding and exposure will be determined at the Near-Surface Test Facility.

8.3.2.7.5 Investigation of radiological monitoring systems

Issues 2.1, 2.2, 2.3, 2.4, and 2.7 relate to the investigation of radiological monitoring systems, which identifies necessary radiation monitoring systems for the repository operations during all phases of operation and under both normal and accident conditions.

8.3.2.7.5.1 Purpose and objectives

The purpose of this investigation is to identify necessary radiation monitoring systems for repository operations during all phases of operation and under both normal and accident conditions. The objective of this investigation is to concentrate on monitoring methods that define worker and public radiation exposure and contamination. Monitoring systems must address the measurement of the following radiation parameters:

- Radiation field strengths and energy spectrums for alpha, beta, gamma, and neutrons.
- Airborne radionuclides.
- Radionuclides in mine water.
- Radionuclides in nuclear waste effluents.
- Criticality.

8.3.2.7.5.2 Rationale

The mined geological disposal system in basalt will be designed, per the direction of 10 CFR 60 (NRC, 1987a), to limit the expected radiation doses to workers during construction, operation, and closure of the repository to less than the allowable limits required by 10 CFR 20 (NRC, 1987b). The specific radiation exposure limits set forth by the NRC are listed in Section 8.3.2.7.3.2.

Monitoring, control, and alarm systems are required by for all radioactive materials (10 CFR 60.131 (a) 4, 5, 6) present in the facility in any form. This investigation is necessary to comply with these regulations.

8.3.2.7.5.3 Description of activities

The required information will be produced as part of the advanced conceptual design and (or) license application design as specified by the Mission Plan (DOE, 1985b). These two design efforts will include radiation monitoring and alarm systems as part of the design. These systems play a critical role in the safe operation of the repository. They are the firstline active systems to sense an off-normal radiation event, initiate the proper

mitigative actions, and warn workers of danger. In addition, proper personal radiation protection devices (e.g., masks, personal dosimeters, clothing) and radiation surveying hand tools will be identified for the workers.

All of these radiation monitoring and alarm systems are the primary devices for sensing releases. The various devices fall into categories for detecting the following:

- Criticality.
- Airborne radionuclides.
- Liquid effluent borne radionuclides.
- Radiation intensity levels.
- Radiation type and energy levels.

The radioactive material flow model for the repository operation will be analyzed in detail, and each physical location, if appropriate, will be identified as needing one or more detectors from the above categories. After the selection of the radiation sensors for a particular area, their role in the automated safety system and degree of redundancy necessary to achieve reliability needs will be determined. The radiation monitor and alarm selections made in the advanced conceptual and license application designs will be reviewed for adequacy using the Q-list methodology developed by the Preclosure Risk Assessment Methodology program.

The design is sensitive to the following site characterization data identified in the issue resolution process. This investigation requires data to be provided by site characterization activities as follows:

- Radionuclide/material removal character of pathways, identified by Issue 2.3; the testing to obtain these data is described in Section 8.3.1.4--Geochemistry.
- Wind speed and direction, identified by Issues 2.1, 2.2, 2.3, and 2.7; the testing to obtain or confirm these data is described in Section 8.3.1.5--Climatology.
- Precipitation, identified by Issues 2.1, 2.2, 2.3, and 2.7; the testing to obtain or confirm these data is described in Section 8.3.1.5--Climatology.
- Host rock shielding, identified by Issues 2.2 and 2.7; the testing to obtain these data is described in Section 8.3.1.2--Geology.
- Radon evolution from the host rock, identified in Issues 2.1, 2.2, and 2.7; the testing of obtain these data is described in Section 8.3.1.2--Geology.

8.3.2.7.5.4 Application of results

The results of this investigation will be used to support the design and performance analysis of the repository, in particular the advanced conceptual design and license application design. In addition, this investigation will provide input for the safety analysis report and environmental impact statement.

8.3.2.7.5.5 Schedule and milestones

The advanced conceptual design will be the next major design phase. Some of the data needs for shielding and exposure will be determined in the Near-Surface Test Facility.

9 2 1 2 5 5 0 5 4 1

This page intentionally left blank.

9 2 1 2 5 5 0 5 4 2

8.3.2.8 Specific program for nonradiological health and safety of workers

This section defines engineering activities or studies necessary to assure that the repository can be designed, constructed, operated, and decommissioned in a manner that provides for the nonradiological health and safety of the workers. To properly address this requirement, the site conditions must be adequately characterized so that sufficient data are available to develop a design and write operating procedures that provide safe conditions for workers during development and operation of the repository. A Preclosure Risk Assessment Methodology program that defines methods of analyzing nonradiological worker safety is discussed in Section 8.3.5.1.

The design, when developed, will be subject to a full safety analysis that will identify accident classes and initiating events. Each of these will be examined in detail to determine causes and effects. Changes to the design, if needed, will be identified and implemented.

Background

National health and safety standards have been issued for the purpose of the protection of life, the promotion of health and safety, and the prevention of accidents. For mines, comprehensive safety standards have been specified in the Federal Mine Safety and Health Administration Act of 1977 (MSHA, 1977, Chapter 1) and 30 CFR 57 (MSHA, 1985).

It should be noted that the memorandum of understanding, dated December 23, 1986, between the DOE and the U.S. Department of Labor, provides a working arrangement whereby the Mine Safety and Health Administration (MSHA) inspects operations of the Office of Civilian Radioactive Waste Management to determine compliance with MSHA standards.

The results of these inspections will be furnished to the DOE to implement its policy of compliance with MSHA standards as though repositories were commercial mines. Necessary actions with the DOE contractors will be taken to assure the prompt and effective correction of any deficiencies and to otherwise ensure general compliance with the MSHA mining health and safety requirements as defined in the Federal Mine Safety and Health Act of 1977.

The National Occupational Safety and Health Administration (OSHA) standards for general industry have been implemented in 29 CFR 1910 (OSHA, 1986), and construction standards are addressed by 29 CFR 1926 (OSHA, 1987).

The U.S. Department of Energy Order 5480.4 (DOE, 1984) specifies and provides requirements for the mandatory environmental protection, safety, and health (ES&H) standards applicable to all DOE and DOE-contractor operations. This order, which shall be followed during facility design, construction, and operation, specifically incorporates 29 CFR 1910 and 29 CFR 1926 as mandatory ES&H standards.

Design criteria with respect to radiological protection and structures system and components important to safety are provided in 10 CFR 60 (NRC, 1987a). With respect to nonradiological health and safety, 10 CFR 60 provides additional design criteria for the underground facility in 10 CFR 60.133(e)(1) stated as follows:

Openings in the underground facility shall be designed so that operations can be carried out safely and the retrievability option maintained.

Additional criteria linked to worker safety are provided for in 10 CFR 60.133 as stated below:

(a) *General criteria for the underground facility...* (2) The underground facility shall be designed so that the effects of credible disruptive events during the period of operations, such as flooding, fires and explosions, will not spread through the facility.

(g) *Underground facility ventilation.* The ventilation system shall be designed to... (2) Assure continued function during normal operations and under accident conditions.

Compliance with the design criteria of 10 CFR 60.133(e), 60.133(a)(2), and 60.133(g)(2) and a number of the requirements of 30 CFR 57 (MSHA, 1985) requires specific information obtainable only by in situ testing at depth in a controlled site characterization program.

Guidance on the relationship between design activities and the above regulations, standards, and site, state, and Federal codes will be provided in the BWIP Safety Plan (DOE/RL, 1987) in which a reference list of applicable safety documentation correlated with the design phases of the repository is provided.

The presence of conditions that could give rise to concern for worker health and safety have been identified and addressed by the SCP repository conceptual design report (KE/PB, 1987b). These conditions include natural occurrences such as flash flooding, seismic events, volcanic ashfall, and severe weather phenomena. Other examples associated with underground construction include rock conditions and stability of the openings, the proximity of bodies of high pressure hot water with dissolved methane, high temperature, and rock characteristics with respect to the release of respirable dust during blasting and muck handling.

Preliminary safety analysis

A preliminary study of preclosure safety concerns (DOE, 1986a) listed applicable regulations, surveyed typical accident scenarios, and provided a preliminary assessment of the consequences. The SCP repository conceptual design report (KE/PB, 1987b) has addressed the subject of safety, and feedback

was provided in the form of identification of events, conditions, and accident-initiating events that could result in violation of repository safety criteria.

Preclosure safety analysis depends on accurate modeling of the systems considered. Such models will include a description of the physical configuration and the process involved. Conceptual models of the systems will be updated as the design changes, and at each design update risks will be evaluated to see how they are changing.

Link to Issues

Section 8.2 uses the issue resolution strategy to establish data needed to design and license a nuclear waste repository in basalt and develop a list of measurable parameters derived from regulatory requirements. Section 8.3.2.8 is linked to the issue resolution strategy through Key Issue 4 and Issue 4.2.

Key Issue 4--"Will the construction, operation (including retrieval), closure, and decommissioning of the mined geological disposal system be feasible at BWIP on the basis of reasonably available technology, and will the associated costs be reasonable in accordance with the requirements set forth in 10 CFR Part 960?" (DOE, 1986c)

Design Issue 4.2--"Are the repository design and operating procedures developed to ensure nonradiological health and safety of workers adequately established for the resolution of the performance issues?" (DOE, 1986c)

Those measures to be adopted by the design, to mitigate or eliminate, where possible, the potential for undue hazards to workers (with respect to the siting considerations of 10 CFR 960 (DOE, 1987b)) were addressed by Issue 4.2.

The parameters that must be measured, analyzed, and evaluated by site characterization activities were compiled into tables in Issue 4.2 (Section 8.2.2.4.2) and will form the basis for the site characterization test program with respect to nonradiological health and safety of workers.

Summary of program

The specific program for nonradiological health and safety of workers as derived from Issue 4.2 consists of one investigation and five subordinate activities or studies. The nonradiological safety program will encompass the safety concerns covered in the MSHA and OSHA regulations. In addition, the unique safety concerns created by nuclear waste handling and nuclear waste retrieval will be resolved.

The documentation for the program is provided in the list of activities and studies in Section 8.3.2.8.3, beginning with the compilation of all applicable nonradiological health and safety requirements. These requirements are then applied to the design activities of the advanced conceptual design and the license application design.

Nonradiological safety-related site characterization data needs will be compiled and a data specification created for each data need, thus providing a documented basis for the testing program. In addition, a construction testing program will be implemented in the Exploratory Shaft Facility. The results from this constructibility program will be used for safety analysis input and to define the safety program. The study will also indicate technical feasibility and potential cost.

8.3.2.8.1 Purpose and objectives

The purpose of the nonradiological health and safety of workers program is to identify the occupational health and safety requirements and to ensure that requirements are used in ongoing design.

The objectives of the program are as follows:

- Identify current and applicable occupational health and safety requirements and the repository design activities they apply to.
- Identify the need to write specific repository requirements.
- Identify the means whereby the advanced conceptual design will reflect all occupational health and safety requirements and identify and incorporate mitigating measures by the use of risk analysis and human factors engineering.
- Identify the ongoing safety program for construction and operations.
- Identify the method of verification of the safety program.

8.3.2.8.2 Rationale

All applicable regulatory and DOE-safety requirements for repository design, construction, and operation will be identified and compiled as a first activity. After all known safety requirements for facilities, components, and operational aspects have been investigated, an analysis will be conducted to identify the unique repository facilities and operations that are not adequately covered by existing safety requirements. This analysis will lead to a new BWIP safety program.

All health and safety-related site characterization data needs or constructibility data needs will be identified.

Repository construction takes place over a long period of time, and is approximately equal to and concurrent with waste emplacement. It is important, therefore, that careful consideration be given to design and construction procedures and to types of equipment used in the construction to achieve the optimum in avoiding undue hazards to repository workers in the following phases and (or) activities:

- Construction, equipping, and commissioning of access shafts.
- Excavation and support of shaft stations and facilities in the pillar area.
- Excavation and support of drifts, rooms, and emplacement openings.
- Ventilation and air-conditioning during development.
- Transportation of personnel, materials, and equipment during development.
- Provision of support services, including utilities, power, communications, instrumentation, monitoring, equipment maintenance, warehousing and supplies, including explosives and fuel.
- Closure activities.

Concurrent waste emplacement activities, also requiring such careful consideration, include the following:

- Waste handling, including ventilation personnel/materials transport, water control, and support services.
- Retrieval, imposing special conditions with respect to the problem of reentry after a room has been sealed off for some time. These conditions are discussed in Issue 2.4, which addresses retrievability, and Issue 2.7, which discusses radiological safety of workers.

8.3.2.8.3 Description of studies and activities

The following subsections define the engineering activities and studies necessary to ensure that the repository can be designed, constructed, operated and decommissioned in a manner that provides for the nonradiological health and safety of workers.

8.3.2.8.3.1 Compilation of applicable nonradiological health and safety requirements

The goal or objective of this activity is to determine applicable non-radiological health and safety requirements. This documentation must include the particular facilities, components, or operations to which the safety requirements apply. The documentation will address, separately, underground, and surface health and safety regulatory requirements, although some overlap is unavoidable. These requirements will provide guidance for the design process and form the basis for nonradiological health and safety design criteria.

8.3.2.8.3.2 Application of nonradiological health and safety requirements to design activities

The objective of this engineering activity is to ensure that the design reflects all of the nonradiological health and safety requirements for both the underground and surface facilities, components, and operations. The output of the previous study is used as input to the design process. As the design develops, task analysis and human factors analysis will be used for sensitive components or operations.

Design and constructibility reviews will be used to verify safety features in the design. In some sensitive areas a more detailed design analysis will be used.

8.3.2.8.3.3 Development of site characterization data needs and specifications

The objective of this engineering activity is to identify all site characterization data needs required for the nonradiological health and safety design aspects of the repository. A data specification will be written from which a testing program can be defined.

Significant site characterization data needs include, but are not limited to, the study and testing of the following:

- Rock mass characteristics and in situ stress ratio as they affect opening stability.
- Hot water, at high pressure with dissolved methane, as it (when liberated) affects the potential for fires and explosions.
- Thickness, lateral extent and continuity, faults, conductive channels, and other anomalies in the host rock as they affect accidental connection of drifts into aquifers.

- Silica content of the rock, the high temperature of the rock, and the blasting characteristics of the rock (fumes, heat, profile irregularity, respirable dust liberated), as all of these parameters relate to adequacy of ventilation and air conditioning.
- Location and vertical extent of aquifers and water pressure as they affect the method of construction, the size, and consequently the number of shafts needed to serve the repository. (Shaft construction and equipping is recognized as a potentially hazardous working environment; hence, more shafts mean more worker exposure.)
- Information on the frequency, aperture, and extent of joints that could cause conducting channels for high-pressure water is needed. Such joints affect the overall quality of the rock mass and its capability to interact in an effective ground support plan. Joint frequency and the rock strength and water chemistry play a key role in grouting procedures. Grouting is used to seal off or reduce potential inflows in advance of the drift face during repository development, or below the bottom of the shaft in conventional shaft-sinking operations.

8.3.2.8.3.4 Development of repository construction and operation safety program document

The goal or objective of this engineering activity is to define the safety program for the repository construction and operation. Since construction and operations will be conducted at the same time, an integrated safety program for both surface and underground activities is needed. The intent is to build safety into all aspects of design, construction, and operations, and then to verify that the systems to maintain safety are in place and can be enforced.

8.3.2.8.3.5 Constructibility study

The study will identify and classify the extent and type of observation, monitoring, and testing to be carried out during construction of the exploratory shafts and the development of the Exploratory Shaft Facility to satisfy design information data needs with respect to nonradiological worker safety.

The objective of this engineering study is to identify all constructibility data needs related to nonradiological health and safety that can be gathered by monitoring progress and performing specific tests during the Exploratory Shaft Facility construction and operation.

Design activities related to underground areas and development have a major impact on nonradiological worker safety. Problem areas occur in access shaft construction and in opening stability. Other problems occur because of the presence of high-pressure hot water, which, if not grouted off, may

liberate gas in potentially explosive concentrations. A further problem is the effect the high rock temperatures (coupled with the presence of water) have on the working environment and the adequacy and quality of the ventilation.

Techniques and equipment approach the limits of reasonably available technology for blind-drilled shafts such that the maximum constructible shaft diameter, coupled with achievable verticality, may not be adequate to accommodate the heavy waste-transfer cask and other hoist system components. Similarly, maximum shaft diameters obtainable by the blind-drilling method may be considerably less than optimum for repository ventilation, thus requiring more shafts to meet the ventilation demand. This causes a safety concern because construction of additional shafts increases the worker exposure, especially during the potentially hazardous shaft-equipping and breakout activities.

A study has been initiated to investigate the alternative of conventional shaft-sinking by freezing or grouting. High temperatures at depth, the presence of water-bearing interbeds containing clays, the rate of strata fluid natural flow, and the rate of fluctuation of the groundwater table level all cause concern. Such examinations that have been carried out indicate that a combination approach using ground freezing would be appropriate to deal with surface deposits, water, and other problem areas in the upper half of the shaft. The use of pregrouting or stage grouting during construction will be investigated to determine if it is appropriate to deal with the heavily water-bearing zones during sinking of the lower half of the shaft. These matters will all be considered in the ongoing study.

Safety and health requirements are discussed in Section 8.2.2.4.2. Safety and health requirements are addressed by the design when tradeoffs are evaluated and performance evaluation is undertaken as per the Design Methodology document (KE/PB, 1987b).

8.3.2.8.4 Application of results

The advanced conceptual design, and subsequently the license application design, will reflect all known health and safety requirements, and the repository design will be modified to reflect results from the testing program related to health and safety features in the design.

The repository construction and operation safety program activities will ensure that safety is integrated into design, construction, and operations.

8.3.2.8.5 Schedule and milestones

The schedule and milestones are to be determined.

8.3.2.9 References

- ACGIH, 1987. Threshold Limit Values for Chemical Substances in the Work Environment Adopted by ACGIH for 1987-1988, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio. [MF 4642]
- ANSI/ASME, 1986. Quality Assurance Program Requirements for Nuclear Facilities, ANSI/ASME NQA-1, American National Standards Institute/American Society of Mechanical Engineers, United Engineering Center, New York, New York. [MF 0680]
- ASTM, 1986a. "Standard Test Method for Creep of Cylindrical Hard Rock Core Specimens in Uniaxial Compression," Annual Book of ASTM Standards, Vol. 04.08, D-4341-84, American Society for Testing and Materials, Philadelphia, Pennsylvania. [MF 4960]
- ASTM, 1986b. "Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression," Annual Book of ASTM Standards, Vol. 04.08, D-3148-86, American Society for Testing and Materials, Philadelphia, Pennsylvania. [MF 4959]
- ASTM, 1986c. "Standard Test Method for Linear Thermal Expansion of Rigid Solids with Vitreous Silica Dilatometer," Annual Book of ASTM Standards, Vol. 03.01, E-228-71, American Society for Testing and Materials, Philadelphia, Pennsylvania. [MF 4961]
- ASTM, 1986d. "Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens without Pore Pressure Measurements," Annual Book of ASTM Standards, Vol. 04.08, D-2664-86, American Society for Testing and Materials, Philadelphia, Pennsylvania. [MF 4958]
- DOE, 1984. Environmental Protection, Safety, and Health Protection Standards, DOE Order 5480.4, U.S. Department of Energy, Washington, D.C. [MF 4849]
- DOE, 1985a. Department of Energy Position on Retrievability and Retrieval for a Geologic Repository, U.S. Department of Energy, Washington, D.C. [MF 4566]
- DOE, 1985b. Mission Plan for the Civilian Radioactive Waste Management Program, DOE/RW-0005, Vol. I, Parts I and II, U.S. Department of Energy, Washington, D.C. [MF 1173]
- DOE, 1986a. Environmental Assessment, Reference Repository Location, Hanford Site, Washington, DOE/RW-0070, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C. [MF 3175]
- DOE, 1986b. Generic Requirements for a Mined Geologic Disposal System, DOE/OGR/B-2, (DOE/RW-0090), Rev. 3, U.S. Department of Energy, Washington, D.C. [MF 4962]

- DOE, 1986c. Systems Engineering Management Plan for the Office of Geologic Repositories, OGR/B-7, U.S. Department of Energy, Washington, D.C. [MF 4963]
- DOE, 1987a. Annotated Outline for Site Characterization Plans, OGR/B-5, DOE/RW-0142, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, Washington, D.C. [MF 4951]
- DOE, 1987b. General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories, Title 10, Code of Federal Regulations, Part 960, U.S. Department of Energy, Washington, D.C. [MF 1953]
- DOE, 1987c. Office of Geologic Repositories Issues Hierarchy for a Mined Geologic Disposal System, OGR/B-10, DOE/RW-0101, Rev. 1, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, Washington, D.C. [MF 4747]
- DOE/RL, 1987. Basalt Waste Isolation Project Safety Plan, DOE/RL 87-08, Rev. 0, U.S. Department of Energy-Richland Operations Office, Richland, Washington.
- Donovan, 1987. Study Plan for Material Model Development, SD-BWI-SP-047, Westinghouse Hanford Company, Richland, Washington. (To be issued)
- EPA, 1986.* Environmental Radiation Protection Standards of Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, D.C. [MF 4906]
- Hibbitt, Karlsson, and Sorensen, Inc., 1985. ABAQUS User's Manual, Version 4.5(a), Hibbitt, Karlsson, and Sorensen, Inc., Providence, Rhode Island. [MF 4500]
- KE/PB, 1987a. Design Methodology, SD-BWI-PBD-003, Rev. 0, Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc. for Westinghouse Hanford Company, Richland, Washington. [MF 4523]
- KE/PB, 1987b. Engineering Study No. 10, Repository Site Characterization Plan Conceptual Design Report, SD-BWI-ES-030, Rev. 0, Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc. for Rockwell Hanford Operations, Richland, Washington. [MF 4546]
- KE/PB, 1987c. Retrievability Strategy Report for Basalt Waste Isolation Project, Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc. for the U.S. Department of Energy, Washington, D.C. [MF 4964]

*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Subpart B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

- Mildon, D. T., 1986. Basalt Waste Isolation Project Mined Geologic Disposal System Design and Development Plan, SD-BWI-PBD-001, Rev. 0, Rockwell Hanford Operations, Richland, Washington. [MF 4965]
- MSHA, 1977. Federal Mine Safety and Health Act of 1977, Public Law 91-173 as amended by Public Law 95-164, 30 U.S.C. 811, Department of Labor, Washington, D.C. [MF 4966]
- MSHA, 1986. Safety and Health Standards-Underground Metals and Nonmetal Mines, Subchapter N, Metal and Nonmetal Mine Safety and Health, Title 30, Code of Federal Regulations, Part 57, Mine Safety and Health Administration, Department of Labor, Washington, D.C. [MF 4905]
- NRC 1985. Generic Technical Position on Design Information Needs in the Site Characterization Plan, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4967]
- NRC 1987a. Disposal of High-Level Radioactive Wastes in Geologic Repositories; Licensing Procedures, Title 10, Code of Federal Regulations, Part 60, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4903]
- NRC, 1987b. Standards for Protection Against Radiation, Title 10, Code of Federal Regulations, Part 20, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4904]
- NWPA, 1983. Nuclear Waste Policy Act of 1982, Public Law 97-425, 96 Stat. 2201, 42 USC 10101, 1983. [MF 4639]
- OSHA, 1986. Occupational Safety and Health Standards, Chapter 17, Occupational Safety and Health Administration, Title 29, Code of Federal Regulations, Part 1910, Department of Labor, Washington, D.C. [MF 4870]
- OSHA, 1987. Safety and Health Regulations for Construction, Chapter 17, Occupational Safety and Health Administration, Title 29, Code of Federal Regulations, Part 1926, Department of Labor, Washington, D.C. [MF 4871]
- Perko, L. N., 1986. Instrumentation Performance Report; NSTF Phase I Testing; Basalt Waste Isolation Project, SD-BWI-TD-026, Rev. 0, Rockwell Hanford Operations, Richland, Washington. [MF 4968]
- Resende, L., 1985. A Damage Mechanics Constitutive Theory for the Inelastic Behavior of Concrete Technical Report No. 64, UCT/CSIR, Applied Mechanics Research Unit, University of Cape Town, Rondebosch, Cape Town, South Africa. [MF 4969]
- RKE/PB, 1983. Conceptual Systems Design Description, Nuclear Waste Repository in Basalt, Protect B-301, SD-BWI-SP-005, Rev. 0-0, 3 Vols., for Rockwell Hanford Operations, Richland, Washington. [MF 2428]

Silling, S. A., 1983. Final Technical Position on Documentation of Computer Codes for High-Level Waste Management, NUREG-0856, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 1049]

St. John, C. M., Aggson, J. R., Hardy, M. P., and G. Hocking, 1982. Evaluation of Geotechnical Surveillance Techniques for Monitoring High-Level Waste Repository Performance, NUREG/CR-2547, Appendix II, J. F. T. Agapito and Assoc. for U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 2486]

9 2 1 2 5 5 0 5 5 4

SITE CHARACTERIZATION PLAN

Chapter 8 - SITE CHARACTERIZATION PROGRAM

Section 8.3.3

Repository Seals Subsystem Program

9 2 1 2 5 5 5 0 5 5 5

9 2 1 2 5 5 0 5 5 6

THIS PAGE
INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
8.3.3 Repository seals subsystem program	8.3.3.1-1
8.3.3.1 Overview	8.3.3.1-1
8.3.3.1.1 Regulations governing the program . . .	8.3.3.1-1
8.3.3.1.2 Issues and issue resolution strate- gies for guiding repository seals subsystem design and development	8.3.3.1-3
8.3.3.1.3 Approach to investigations	8.3.3.1-6
8.3.3.1.4 Organization of Section 8.3.3	8.3.3.1-8
8.3.3.2 Specific program to characterize repository seals subsystem environment	8.3.3.2-1
8.3.3.2.1 Investigation to compile data on site, repository, and engineered barriers subsystems	8.3.3.2-2
8.3.3.2.2 Investigation to compile damaged rock zone data	8.3.3.2-6
8.3.3.3 Specific program for repository seals sub- system components and interactions testing	8.3.3.3-1
8.3.3.3.1 Investigation for laboratory testing of barrier materials properties and interactions	8.3.3.3-2
8.3.3.3.2 Investigation for field testing of barrier materials properties and development of barrier emplacement methods	8.3.3.3-11
8.3.3.4 Specific program for repository seals subsystem design optimization	8.3.3.4-1
8.3.3.4.1 Investigation to select barrier materials, configurations, and locations	8.3.3.4-2
8.3.3.4.2 Investigation to develop barrier installation procedures	8.3.3.4-8
8.3.3.5 Specific program for repository seals subsystem modeling	8.3.3.5-1
8.3.3.5.1 Performance sensitivity investigation	8.3.3.5-2
8.3.3.5.2 Performance assessment investigation	8.3.3.5-16
8.3.3.6 References	8.3.3.6-1

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.3.3-1	Laboratory testing of barrier materials, properties, and interactions	8.3.3.3-3
8.3.3.3-2	Schedule of studies for laboratory testing	8.3.3.3-12
8.3.3.3-3	Field testing of barriers materials properties and demonstration of barrier emplacement methods	8.3.3.3-13
8.3.3.3-4	Boreholes drilled from the extensometer room to the heater test room in the Near-Surface Test Facility	8.3.3.3-17
8.3.3.3-5	Schedule of studies and activities for field testing	8.3.3.3-20
8.3.3.4-1	Selection of barrier materials, configurations, and locations	8.3.3.4-3
8.3.3.4-2	Schedule of activities for selection of barrier materials, configurations, and locations	8.3.3.4-9
8.3.3.4-3	Development of barriers installation procedures	8.3.3.4-10
8.3.3.4-4	Schedule of activities for development of barrier installation procedures	8.3.3.4-12
8.3.3.5-1	Performance sensitivity analyses for the repository seals subsystem	8.3.3.5-3
8.3.3.5-2	Use of the PORFLO computer code in assessing the repository seals subsystem performance and supporting analyses of cumulative radionuclide releases from the overall repository system	8.3.3.5-8
8.3.3.5-3	Use of the MAGNUM-2D and CHAINT computer codes in assessing the repository seals subsystem performance and supporting analyses of cumulative radionuclide releases from the overall repository system . .	8.3.3.5-11
8.3.3.5-4	Schedule of activities for sensitivity analyses	8.3.3.5-15
8.3.3.5-5	Performance assessment activities for the repository seals subsystem	8.3.3.5-17
8.3.3.5-6	Schedule of activities for performance assessment	8.3.3.5-23

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.3.2-1	Site, repository, and waste package data judged as needed to acquire information for repository seals subsystem design and performance assessments . . .	8.3.3.2-4
8.3.3.2-2	Damaged rock zone data judged as needed to acquire information for repository seals subsystem design and performance assessments	8.3.3.2-8
8.3.3.5-1	Principal computer codes and variants to be used for repository seals subsystem analysis	8.3.3.5-7
8.3.3.5-2	Computer codes that may be used for ancillary analyses of the repository seals subsystem	8.3.3.5-10

This page intentionally left blank.

9 2 1 2 5 5 5 0 5 6 0

8.3.3 REPOSITORY SEALS SUBSYSTEM PROGRAM

This section describes the investigations that form the Basalt Waste Isolation Project (BWIP) program for postclosure sealing of the repository. These investigations are based on the strategy discussed in Section 8.2.2.1.12 for repository seals subsystem design and development. The purpose of the strategy is to address the U.S. Department of Energy (DOE) issues (DOE, 1987) that must be resolved to demonstrate compliance with applicable Federal regulations and to support site selection and licensing for a mined geologic disposal system in basalt. Sealing of subsurface repository openings will be needed to provide reasonable assurance that the repository will comply with (1) the U.S. Environmental Protection Agency (EPA) regulation (EPA, 1986) limiting cumulative postclosure releases of radionuclides to the accessible environment and (2) the U.S. Nuclear Regulatory Commission (NRC) regulations for geologic disposal of high-level radioactive waste (NRC, 1987). Furthermore, a repository seals subsystem design and development program is needed to address the six concerns of the NRC generic technical position on borehole and shaft sealing of high-level nuclear waste repositories (NRC, 1986).

8.3.3.1 Overview

This overview summarizes the regulatory basis and describes the functions of repository barriers for postclosure sealing of a geologic disposal system mined in basalt. It also states the scope, rationale, and technical approach of the BWIP repository seals subsystem program and indicates the interfaces of this program with other BWIP site characterization and repository design programs. This overview includes the following:

- Regulations governing the program (Section 8.3.3.1.1).
- Issues and issue resolution strategies for guiding repository seals subsystem design and development (Section 8.3.3.1.2).
- Approach to investigations (Section 8.3.3.1.3).

8.3.3.1.1 Regulations governing the program

The NRC regulations for geologic disposal of high-level radioactive waste are given in 10 CFR 60 (NRC, 1987). Regulations for repository seals subsystem design are stated in 10 CFR 60.134 as follows:

- a) General design criterion. Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives for the period following permanent closure.

- b) Selection of materials and emplacement methods. Materials and placement methods for seals shall be selected to reduce, to the extent practicable: (1) the potential for creating a preferential pathway for groundwater to contact the waste packages; or (2) for radionuclide migration through existing pathways.

These repository seals subsystem performance requirements are related to overall repository system performance requirements stated in 10 CFR 60.112 (NRC, 1987) as follows:

The geologic setting shall be selected and the engineered barriers system and the shafts, boreholes, and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the EPA with respect to both anticipated processes and events and unanticipated processes and events.

Regulations for testing of repository seals subsystem designs are defined in 10 CFR 60.142 (NRC, 1987) as follows:

- a) During the early or developmental stages of construction, a program for in situ testing of such features as borehole and shaft seals, backfill, and the thermal interaction effects of the waste packages, backfill, rock, and groundwater shall be conducted.
- b) The testing shall be initiated as early as practicable.
- c) A backfill test section shall be constructed to test the effectiveness of backfill placement and compaction procedures against design requirements before permanent backfill placement is begun.
- d) Test sections shall be established to test the effectiveness of borehole and shaft seals before full-scale operation proceeds to seal boreholes and shafts.

In situ testing of the repository seals subsystem to verify the designs will be conducted following construction authorization and therefore is not within the scope of site characterization.

The rationale used by the NRC in developing the 10 CFR 60 regulations pertaining to sealing is given in the Generic Technical Position on Borehole and Shaft Sealing of High-Level Nuclear Waste Repositories (NRC, 1986, Section 5.0). This document states that postclosure shaft and borehole sealing shall attain the following:

- The EPA standard (EPA, 1986) for cumulative radionuclide releases from nuclear waste repositories as part of the overall repository system.

- Hydraulic conductivities in the sealed zone as low as or at least approaching that of the rock units mass or as low as can reasonably be achieved and still not compromise repository performance; or retardation of radionuclides which at least approaches that of the host rock.
- Chemical and physical compatibility and stability with the host rock units and groundwater chemistry or, if alterations occur to the original barrier characteristics, assurance that these alterations will not compromise repository seals subsystem performance.
- Ability to adequately and confidently assess repository seals subsystem performance for the life of the repository.

In addition, the NRC generic technical position (NRC, 1986, Section 3) identifies the following concerns regarding sealing:

- Long-term stability of barriers.
- Design of shafts and boreholes with consideration for long-term sealing.
- Installation procedures for sealing.
- Impact of waste-induced thermal loading on barriers.
- Compatibility of barriers to host rock environment.
- Maintaining low hydraulic conductivities in the sealed area.

8.3.3.1.2 Issues and issue resolution strategies for guiding repository seals subsystem design and development

The repository seals subsystem program is guided by Issue 1.12, Seals (DOE, 1987), which is stated as follows:

Have the characteristics and configurations of the shaft and borehole seals been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.134 and (b) provide information for the resolution of the performance issues?

The performance issue with which Issue 1.12 interfaces is Issue 1.1, Release to Accessible Environment (see Section 8.2.2.1.1).

The detailed strategy for resolving Issue 1.12 and the interface with Issue 1.1 is given in Section 8.2.2.1.12. A summary of the strategy is presented below.

Deep geologic disposal of high-level radioactive waste will require penetration of the candidate site for access to emplace nuclear waste. After closure of the subsurface facility, these penetrations become potential pathways for transport of radionuclides to the accessible environment in quantities that may exceed those allowed. To ensure isolation of the waste from the accessible environment, such penetrations will require sealing to prevent them from becoming preferential pathways for groundwater flow and radionuclide migration.

The question that must be answered by the repository seals subsystem design and development program is whether barriers to groundwater flow and radionuclide transport through the subsystem pathways are adequate to comply with the EPA standard for cumulative radionuclide releases to the accessible environment. The implementation of activities proposed to answer the question will be guided by a strategy of allocating goals for performance to barriers installed in pathways for transport of radionuclides through the seals subsystem to the accessible environment. These goals are not to be confused with regulatory criteria or standards. They are tentative specifications whose purpose is to guide design and (or) data collection activities needed to resolve Issue 1.12. The goals are subject to change in accordance with implementation of program options.

Underground openings excavated during repository construction and operation, and boreholes drilled during or subsequent to repository construction and operation, are potential preferential pathways for groundwater flow and radionuclide migration that may adversely affect performance of the repository. The repository seals subsystem consists of barriers placed in the underground openings and, if necessary, in the annulus of damaged rock surrounding the openings, to retard groundwater flow and radionuclide migration to the accessible environment. Current designs of repository seals subsystem elements are described in Chapter 6.

Underground openings that may require sealing include shafts providing access from the Earth's surface to the underground facility, drifts providing access and ventilation to the waste emplacement rooms, and boreholes within the controlled area that originate either from the Earth's surface or from underground excavations. Waste emplacement rooms and backfill placed in these rooms are specifically excluded from the repository seals subsystem.

8.3.3.1.2.1 Allocation of performance goals and confidences needed to resolve Issue 1.1

The performance goal for the repository seals subsystem is stated in terms of postclosure performance of the overall repository system. To help resolve Issue 1.1, allocations of barrier functions and associated performance goals for the repository seals subsystem are necessary at three levels of detail: (1) the repository system, (2) repository seals subsystem, and (3) specific barriers and barrier components for all significant pathways of the repository seals subsystem.

The strategy for resolving Issue 1.1 includes allocation of a performance goal and needed confidence to the repository seals subsystem (see Section 8.2.2.1.1). This goal is arbitrarily assigned and subject to change. The goal is as follows:

Limit radionuclide releases through all repository seals subsystem pathways to 1% or less of the EPA's maximum allowable limit for cumulative radionuclide releases to the accessible environment, at the confidence levels specified by the EPA (1986, 40 CFR 191.13).

This subsystem performance goal is the maximum cumulative radionuclide release to the accessible environment that would be allowed through all transport pathways created by excavated openings. The goal is judged to be sufficiently strict that, if met, the repository seals subsystem could not be a preferential pathway (NRC, 1987, 10 CFR 60.134) for transport of radionuclides to the accessible environment.

To develop design specifications for components of repository seals subsystem barriers, the functions of the barrier components must be identified and performance goals must be allocated at a level of detail greater than that of the overall subsystem. An assignment of functions to be performed by barriers and their components, and allocation of goals for the performance of those functions, is detailed in Section 8.2.2.1.12.

To assure acceptable performance, individual performance goals based on sensitivity analyses must be assigned to each potential preferential pathway of the subsystem for expected and unexpected transport processes, events, and repository conditions. Like the subsystem performance goal, these pathway barrier goals are not to be confused with regulatory criteria or standards. They are tentative specifications intended to guide design or data collection activities and, as such, are subject to change. The pathway barrier performance goals are arbitrarily assigned as follows:

- Seventy-five percent of the subsystem goal for the potential pathway through the entry drifts and shafts.
- Twenty-five percent of the subsystem goal for the potential pathway through boreholes in the controlled zone.

These goals are based on current engineering judgment and may change as knowledge of the repository seals subsystem capabilities grows.

The pathways of the entry drifts and shafts will be blocked by drift barriers and shaft barriers. Permanent sealing of the shafts would likely require removal of shaft liners and grout. Because of technical difficulties, high costs, questions of occupational safety, and uncertainty of effects on hydraulic properties of the damaged rock zone that would likely result from liner removal, an initial design premise is that the liner will not be removed and both entry drift and shaft barriers will be needed to impede transport of radionuclides along the shaft pathway.

9 2 1 2 5 5 5 0 5 6 5

Each pathway barrier will be designed and analyzed in terms of three components: (1) backfill in the openings, (2) the interface between the backfill and the annulus of damaged rock around the opening, and (3) damaged rock around the opening. Performance goals for components needed to achieve the barriers performance goal are defined by values assigned to parameters that characterize each component (see Section 8.2.2.1.12).

8.3.3.1.2.2 Additional design goals and reliabilities needed to resolve Issue 1.12

Identification and justification of which additional repository seals subsystem design optimization information will be needed to resolve Issue 1.12 is determined by a process analogous to that used to identify repository seals subsystem information needed to resolve Issue 1.1. In fact, the allocation that provides the rationale for work needed to resolve Issue 1.12 also defines many of the underlying premises for the conceptual radionuclide transport models and barrier designs used by sensitivity analyses to derive the performance goals and needed confidences identified in Section 8.2.2.1.12 (Tables 8.2.2.1.12-3 and 8.2.2.1.12-4). Table 8.2.2.1.12-5 (Section 8.2.2.1.12) shows the additional information needed for resolution of Issue 1.12.

8.3.3.1.3 Approach to investigations

Postclosure repository barriers will not be installed before expiration of the 50-yr period for waste retrievability after waste-emplacement operations begin (or a different time period as established by the NRC). Therefore, the principal objective of the repository seals subsystem program, during the period leading up to the application for a license to receive and emplace high-level nuclear waste, is to determine if a repository in basalt can be sealed in compliance with regulatory requirements. This determination will depend on the results of repository, waste package, and repository seals subsystem design; performance assessment; laboratory testing of barrier materials; field testing of barrier emplacement methods; and in situ performance confirmation testing. Because the scope of the Site Characterization Plan (SCP) is restricted to plans for investigations needed for site characterization, plans for some aspects of design optimization, verification testing, and performance confirmation are described in the subsurface closure engineering plan (McCarthy, 1987).

Although installation of postclosure repository barriers would not begin until at least 50 yr after initial waste emplacement, barrier designs and installation procedures must be developed, and their feasibility and effectiveness established, as part of the process for site selection and construction authorization. Principal BWIP milestones controlling the

schedule for repository seals subsystem program investigations are the following:

- Issuance of the final Environmental Impact Statement.
- Issuance of the Site Selection Report.
- Submittal of the license application for repository construction to the NRC.

To meet these milestones, many repository seals subsystem program activities must be initiated and completed in parallel. Consequently, assessment of barrier performance, testing and selection of barrier materials and installation methods, and development of barrier design concepts are interdependent.

The primary objective of repository sealing activities during the period preceding license application for construction authorization is to develop viable sealing concepts that comply with postclosure performance criteria. Materials testing, field testing of equipment and procedures for installation, in situ testing of repository environmental conditions, and performance analyses will guide the selection of materials, configurations, locations, and installation techniques for postclosure repository barriers.

Advanced conceptual and license application designs for the repository seals subsystem will be completed in concert with analogous designs for the repository.

Determination of the physical properties of barrier materials, as needed to select materials for the license application design and assess that design's performance, will be made during the early part of the site characterization phase. Laboratory testing to determine long-term behavior of barrier materials will be conducted during the latter part of the site characterization phase and continue as necessary to confirm the adequacy of materials selection or to help optimize barrier designs prior to final decommissioning. Some materials characterization activities will depend on the results of in situ testing and (or) design development and, therefore, will extend beyond the site characterization phase.

Collection of data to determine site environmental conditions and waste package parameters important to the repository seals subsystem program will continue throughout site characterization.

Field testing of barrier design concepts will be scheduled to develop installation techniques and demonstrate equipment adequacy for selected barrier components. Results of field testing will be used to partially optimize the license application design and to aid in planning of in situ performance confirmation testing. Such performance confirmation testing would begin following construction authorization.

Assurance of barrier design adequacy cannot be obtained entirely through in situ performance confirmation testing because of the long durations required for (1) waste containment, (2) groundwater and radionuclide transport, and (3) specified repository design lifetime. Reliance must be placed on modeling and performance assessment to confirm design adequacy and compliance with functional requirements for the repository seals subsystem.

The initial phase of performance assessment activities will consist primarily of (1) allocation and refinement of performance goals for the seals subsystem and its components and (2) sensitivity analyses to determine the relative importance of parameters governing repository seals subsystem performance. The primary objective of performance assessment during this phase is to guide the design process. This phase of performance assessment will support definition of requirements for license application design. As barrier designs are developed and as site characterization activities proceed, performance goals will be reexamined to provide feedback to the design process and performance assessment and to supply information for site selection and licensing. These activities will continue until license application for construction authorization.

For detailed discussions and schedules of the activities planned for the repository seals subsystem program, refer to Sections 8.3.3.2 through 8.3.3.5.

8.3.3.1.4 Organization of Section 8.3.3

The schedule information provided for investigations in this program includes the sequencing, interrelationships, and relative durations of the studies in the investigation. Specific durations and start/finish dates for the studies are being developed as part of ongoing planning efforts and will be provided in the SCP at the time of issuance and revised as appropriate in subsequent semiannual progress reports.

The repository seals subsystem program comprises four specific programs. Section 8.3.3.2 identifies the data required to establish the repository seals subsystem environment. The objective of this program is to identify, in conjunction with the parameter tables in Section 8.2.2.1.12, the physical and chemical characteristics that influence the design and performance of the repository seals subsystem and to identify the site characterization activities that will provide the data.

Section 8.3.3.3 identifies and describes the seal subsystem component and interaction testing. The objective of this program is to support barrier materials selection and performance analysis through laboratory testing, and to support design through testing of barrier materials installation techniques.

Section 8.3.3.4 identifies and describes the repository seals subsystem design optimization activities that will require site characterization data. The objectives of this program are to select barrier materials, configurations, and locations and to develop the methods for installing these barriers.

Section 8.3.3.5 describes the plans for activities to assess the postclosure performance of the repository seals subsystem. The objective of this program is to focus and guide subsystem design and laboratory and field testing by assessing subsystem performance against regulatory requirements.

9 2 1 2 5 5 5 0 5 6 9

This page intentionally left blank.

9 2 1 2 5 5 5 0 5 7 0.

8.3.3.2 Specific program to characterize repository seals subsystem environment

The objectives of this repository seals subsystem program are to identify information needs and compile data pertinent to the repository seals subsystem environment. Data of interest are site geology, hydrology, geochemistry, host rock thermal and mechanical properties, in situ stress and temperature, repository design features that affect sealing of excavated openings, radionuclide species and their concentrations that may be released to the repository seals subsystem, and properties of the damaged rock zone.

Of particular concern to postclosure sealing are the properties of the damaged rock zone. The damaged rock zone, as defined for purposes of repository sealing, is that rock adjacent to a shaft, drift, or borehole in which the hydrologic properties (hydraulic conductivity and effective porosity) have been modified by the excavation process. These changes in hydraulic properties may result from blast damage, stress redistribution, and subsequent interaction between the ground support subsystem, repository seals subsystem barriers and the surrounding rock. Discussions of damaged rock zone investigations are separated from those of other site characterization investigations because of the sensitivity of repository seals subsystem performance to hydrologic properties of the damaged rock zone.

Background

Identification of parameters required for repository seals subsystem design and analysis was discussed in Section 8.2.2.1.12. This identification was based on the current seals designs (see Chapter 6) and performance sensitivity analyses (Section 8.3.3.5). Because the identified parameters are encompassed within much of the site characterization program (e.g., geology, rock characteristics, hydrology, geochemistry), the scope of this section is limited to listing the parameters required for characterizing the repository seals subsystem environment and identifying the investigations and studies that will provide those parameters.

Summary of program

This section identifies the data required to characterize the environments in which repository seals subsystem pathway barriers will be emplaced. The repository seals subsystem program comprises two investigations to characterize the barriers emplacement environment: (1) compilation of site, repository, and waste package data, and (2) compilation of damaged rock zone characterization data. These investigations will entail no testing or analysis by the repository seals subsystem program; the data will be obtained from other BWIP programs. Identification of data requirements will be iterative and guided by the process of allocating goals for performance and design of repository seals subsystem barriers (see Section 8.2.2.1.12).

Section 8.3.3.2.1, Investigation to compile data on the site, repository, and engineered barrier subsystems, lists the parameters identified in Section 8.2.2.1.12 as required for repository seals subsystem design and analysis. It also identifies the sections within this document that discuss the investigations and studies that will obtain the data. Section 8.3.3.2.2, Investigation to compile damaged rock zone data, lists the parameters identified in Section 8.2.2.1.12 as required to characterize the damaged rock zone for the purpose of repository seals subsystem design and analysis. Also included are the references to the sections within the document that discuss the investigations and studies that will obtain the data.

8.3.3.2.1 Investigation to compile data on site, repository, and engineered barriers subsystems

The environment of emplaced barriers will affect barrier design and performance. This section identifies a tentative list of data needed to describe that environment and sources for the data.

8.3.3.2.1.1 Purpose

The purpose of this investigation is to provide data pertinent to the locations, designs and performances of barriers, and identification of testing needed to confirm materials properties and expected performance of barriers. Identification of required data is by the process outlined in Section 8.2.2.1.12.2. The objectives of this investigation are to identify the studies that will obtain the site, repository, and engineered barriers data needs identified in Tables 8.2.2.1.12-3 through 8.2.2.1.12-5 and compile the data from these studies.

8.3.3.2.1.2 Rationale

The basis for determining which information on the repository seals subsystem environment is needed was given in Section 8.2.2.1.12. Data on site and engineered barriers subsystems, and repository layout and design (see Tables 8.2.2.1.12-3 through 8.2.2.1.12-5) are needed for barriers design and performance assessment.

No alternatives to compiling the required data from other BWIP programs are identified. Alternative technical approaches to obtaining the data are, or will be, discussed in the study plans specific to each investigation.

A significant constraint on the program for characterization of the repository seals subsystem environment is the need to access parts of the underground facility for mapping and testing. Constraints on the scheduling of data collection programs may require that some aspects of repository seals subsystem design and performance assessment either be delayed or initially be based on expert engineering judgment.

8.3.3.2.1.3 Description of activity

The programs that will obtain the data to be used in characterizing the repository seals subsystem environment are described in the following sections:

- Site program (Section 8.3.1).
- Site geology (Section 8.3.1.2).
- Site hydrology (Section 8.3.1.3).
- Site geochemistry (Section 8.3.1.4).
- Repository program (Section 8.3.2).
- Verification or measurement of environment (Section 8.3.2.2).
- Coupled interaction tests (Section 8.3.2.3).
- Design optimization (Section 8.3.2.4).
- Repository modeling (Section 8.3.2.5).
- Waste package program (Section 8.3.4).
- Waste package environment (Section 8.3.4.2).
- Waste package components and interaction testing (Section 8.3.4.3).
- Waste package design development (Section 8.3.4.4).
- Waste package modeling (Section 8.3.4.5).

A list of the data currently judged as needed to acquire the parameters specified in Tables 8.2.2.1.12-3 through 8.2.2.1.12-5 is given in Table 8.3.3.2-1. As repository seals subsystem designs evolve and performance assessments are refined, data needs will be reevaluated by additional sensitivity analyses and modeling (see Sections 8.3.3.5.1 and 8.3.3.5.2), and required changes will be incorporated into program plans.

8.3.3.2.1.4 Application of results

The locations, sizes, shapes, methods, and sequences of barrier component construction (Sections 8.3.3.4.1 and 8.3.3.4.2) will be controlled largely by the design of the facility and geology of the barrier location. Barrier performance goals (see Section 8.3.3.1.2) will be affected by site hydrology, geology, temperature, and concentrations of the radionuclides at specific sealing locations. Materials selection (Section 8.3.3.4.1) will depend on data from all of these aspects, particularly hydrology and geoengineering. Material selection must take into account not only long-term stability in the repository environment but also stability during resaturation of the repository horizon. Geochemistry and geology will contribute data required to demonstrate barrier material compatibility (Section 8.3.3.3.1) with the host environment.

Repository seals subsystem performance modeling (Sections 8.3.3.5) and damaged rock zone characterization (Section 8.3.3.2.2) also require data on the repository seals subsystem environment. Barriers performance, measured by cumulative radionuclide releases through the subsystem, will depend on the hydrologic characteristics of the sealed areas and the species and concentrations of radionuclides that reach the repository seals subsystem. Modeling of the damaged rock zone will require data describing in situ stress, thermomechanical rock properties, hydrologic properties, and information on facility design.

Table 8.3.3.2-1. Site, repository, and waste package data judged as needed to acquire information for repository seals subsystem design and performance assessments (also see Tables 8.2.2.1.12-3 through 8.2.2.1.12-5) (sheet 1 of 2)

Data required	Data sources (Site Characterization Plan section)	Applications in seals subsystem program
Stratigraphy in shafts and boreholes: <ul style="list-style-type: none"> • Structure • Depths of stratigraphic units • Thicknesses of stratigraphic units 	Stratigraphic framework of the controlled area study zone (1.2.2), Stratigraphy and structure investigation (8.3.1.2.3), Stratigraphy study (8.3.1.2.3.1), Intraflow structure study (8.3.1.2.3.2), Structural geology study (8.3.1.2.3.4), Stratigraphic and structural model study (8.3.1.2.3.6)	Locations of shafts and boreholes barriers, selection of barriers materials compatible with host rock
Groundwater composition: <ul style="list-style-type: none"> • Major, minor, and trace ions • Eh, pH Groundwater composition changes (post-emplacement)	Isotopic and regional hydrochemistry (3.7.3), Hydrochemistry (3.9.1.3), Groundwater geochemistry (4.1.2), Geochemical effects of waste emplacement (4.2), Hydrochemical characterization investigation (8.3.1.4.3), Groundwater flow system hydrochemistry study (8.3.1.4.3.1), Groundwater redox characteristics study (8.3.1.4.3.2)	Barriers materials selection, longevity testing, and modeling
Groundwater temperature (in individual hydrostratigraphic units penetrated by shafts and boreholes) Natural geothermal gradient	Geothermal regime (1.3.2.5), Temperature and pressure (4.1.2.8), Site groundwater study (8.3.1.3.4.3.2)	Barriers materials longevity testing and modeling, thermomechanical analysis
Hydrostatic pressures in shafts, boreholes, and drifts where barriers may be emplaced	Potentiometric levels (3.6.3), Potentiometric levels (3.9.1.2), Site groundwater study (8.3.1.3.4.3.2)	Performance modeling, barriers design
Hydrologic properties of Grande Ronde Basalt flows and Frenchman Springs (flow interiors, tops, and bottoms) <ul style="list-style-type: none"> • Hydraulic gradient • Effective porosity • Hydraulic conductivity Anisotropy ratio for Grande Ronde Basalt dense interior	Site groundwater study (8.3.1.3.4.3.2)	Allocation of performance goals, performance modeling
Sorptive behavior of host rock	Geochemical retardation processes (4.1.3), Radionuclide retardation behavior investigation (8.3.1.4.4)	Performance modeling
In situ stresses at barrier locations Seismicity: <ul style="list-style-type: none"> • Shear wave velocity • Compression wave velocity • Damping 	Existing stress regime (2.6), In situ stress study (8.3.2.2.3.1), Seismology of candidate area and site (1.4), Long-term regional stability with respect to tectonics and geologic processes (1.5), Seismology study (8.3.1.2.4.3.2)	Thermomechanical analysis, selection of barriers designs and materials to resist imposed loads, damaged rock zone assessment
Mechanical, thermal, and thermomechanical properties of intact rock and rock mass: <ul style="list-style-type: none"> • Intact rock strength and deformability at barriers locations • Rock mass deformability • Failure criteria • Thermal conductivity • Specific heat (heat capacity) • Thermal expansion coefficient 	Mechanical properties of rock units - intact rock (2.1), Mechanical properties of rock units - discontinuities (2.2), Mechanical properties of rock units - large scale (2.3), Thermal and thermomechanical properties - intact rock (2.4), Thermal and thermomechanical properties - large scale (2.5), Thermal/thermomechanical properties study (8.3.2.2.3.2), Mechanical properties study (8.3.2.2.3.3)	Thermomechanical analysis, selection of barriers designs and materials to resist imposed loads, damaged rock zone assessment

PST87-2005-8.3.3-15

Table 8.3.3.2-1. Site, repository, and waste package data judged as needed to acquire information for repository seals subsystem design and performance assessments (also see Tables 8.2.2.1.12-3 through 8.2.2.1.12-5) (sheet 2 of 2)

Data required	Data sources (Site Characterization Plan section)	Applications in seals subsystem program
Repository design: <ul style="list-style-type: none"> • Depth of facility • Design of shafts, drifts and boreholes • Locations and orientations of openings relative to geologic structures and hydraulic gradients • Dimensions of openings • Presence and locations of liners or casing • Presence and locations of rock supports • Drilling and excavation techniques • Waste emplacement mode 	Current repository design description (6.2), Design optimization (8.3.2.4), Repository modeling (8.3.2.5)	Locations of barriers, compatibility with repository design, conditions of openings to be sealed
Radionuclide inventory, concentrations, and species at potential barriers locations	Geochemical retardation processes (4.1.3), Waste form information activity (8.3.4.3.3.1), Radionuclide solubility/sorption and speciation behavior study (8.3.4.3.6.3.1), Radionuclide release and transport sensitivity analysis (8.3.4.5.3.3.4), Radionuclide release and transport analysis (8.3.4.5.4.3.4)	Allocation of performance goals, performance modeling, stability of materials exposed to radiation
Locations and characteristics of all drill holes and excavations at and near the site	Drilling and mining (1.6)	Locations of barriers, performance modeling

PST87-2005-8.3.3-15

8.3.3.2.1.5 Schedule

Compilation of data needed by the repository seals subsystem program will be a continuous process. Refer to the sections cited in Table 8.3.3.2-1 and Section 8.5 for the schedules of activities planned to obtain data on the environment of the repository seals subsystem.

8.3.3.2.2 Investigation to compile damaged rock zone data

Excavating shafts and entry drifts may change the properties of the host rock surrounding the excavations. Conventional drill-and-blast techniques and blind-hole drilling can fracture the host rock. Stress redistribution can dilate fractures near excavated openings. These changes can increase hydraulic conductivity and effective porosity.

This section lists the data needed to characterize the damaged rock zone for purposes of the repository seals subsystem program and identifies the sources for that data.

8.3.3.2.2.1 Purpose and objectives

The purpose of this investigation is to compile damaged rock zone data that are pertinent to repository seals subsystem design and performance assessment. Identification of required data is by the process outlined in Section 8.2.2.1.12.2. The objectives of this investigation are to identify the studies that will obtain the damaged rock zone data needs identified in Tables 8.2.2.1.12-3 through 8.2.2.1.12-5 and compile the data from these studies. Because performance of the repository seals subsystem is very likely sensitive to hydraulic properties of the damaged rock zone (Seitz et al., 1986), identification of subsystem needs for data on the damaged rock zone will be updated periodically as barrier designs and assessments of seals subsystem performance are refined.

8.3.3.2.2.2 Rationale

Data on the damaged rock zone contribute to barrier design and performance assessment. Damaged rock zone data are also required to address EPA (1986) and NRC (1987) regulations and the NRC generic technical position issues for borehole and shaft sealing (NRC, 1986). The basis for the determination of information needs for the damaged rock zone was given in Section 8.2.2.1.12.

The alternative to compiling data on the damaged rock zone would be to develop coupled geomechanical and fluid-flow computer codes and rely on their predictive capacity with only limited validation through laboratory testing. This alternative has been rejected because of the high level of uncertainty associated with the use of numerical modeling techniques not properly supported by investigation and measurement of geomechanical and hydrologic properties of the damaged rock at repository depth. A second alternative to

compiling data on the damaged rock zone from other tests within the Exploratory Shaft Facility would be to design and conduct in situ tests to specifically measure the properties of the damaged rock zone at the seals locations. During the advanced conceptual design, a study will be conducted to evaluate the type of testing required and the schedule for this testing (Section 8.3.3.4.1.3).

A significant constraint on the program to characterize the damaged rock zone is the need for access to underground facilities to obtain pertinent data. Constraints on the scheduling of tests and data collection programs may require that some aspects of barriers design and performance assessment be delayed or initially based on expert engineering judgment. Constraints on the technical aspects of data collection are addressed in the parts of this plan specific to collection of geologic and hydrologic data.

8.3.3.2.2.3 Description of activity

Analyses of the sensitivity of performance of drift and shaft barriers (Seitz et al., 1986) to hydraulic properties of the damaged rock zone have been completed. Performance of the repository seals subsystem was indicated by this study to be very sensitive to the hydraulic properties of the damaged rock zone. Hence, sealing of the damaged rock zone, if required, will be highly dependent on the characteristics of the damaged rock zone.

Because there are several other applications for data on the damaged rock zone (e.g., rock support design, blasting design, and selection of excavation method (Section 8.3.2)), programs other than repository seals subsystem design and development (e.g., Site Hydrology, Section 8.3.1.3) will provide the data needed for repository seals subsystem design and performance assessment.

The programs and areas of study from which the data to characterize the damaged rock zone will be collected are described in the following sections:

- Site hydrology (Section 8.3.1.3).
- Verification or measurement of host rock environment (Section 8.3.2.2).

A list of data currently judged as needed to acquire the information specified in Tables 8.2.2.1.12-3 through 8.2.2.1.12-5 is given in Table 8.3.3.2-2. As the repository seals subsystem design evolves and sensitivity analyses and performance assessments are refined, data needs will be reassessed by additional sensitivity analyses and modeling (Sections 8.3.3.5.1 and 8.3.3.5.2). Based on the results of these updated analyses, the repository seals subsystem program will provide appropriate guidance to other BWIP programs to assure collection of data needed for postclosure repository sealing.

Table 8.3.3.2-2. Damaged rock zone data judged as needed to acquire information for repository seals subsystem design and performance assessments (also see Tables 8.2.2.1.12-3 through 8.2.2.1.12-5)

Data required	Data sources (Site Characterization Plan section)	Applications in seals subsystem program
Geomechanical properties of damaged rock zone	Mechanical properties of rock units - discontinuities (2.2), Strength of rock mass (6.3.4), Specific program to verify or measure host rock environment (8.3.2.2), Opening performance stability study (8.3.2.2.3.4)	Development of geomechanical models of the damaged rock zone
Structural features of damaged rock zone (fractures) <ul style="list-style-type: none"> • Frequency and spacing • Aperture • Orientation • Continuity 	Structural geology and tectonics of candidate area and site (1.3), Mechanical properties of rock units - discontinuities (2.2), Mechanical properties study (8.3.2.2.3.3)	Barriers design, development of geomechanical and hydrologic models for the damaged rock zone
Hydraulic conductivity and effective porosity of the damaged rock zone	Site groundwater study (8.3.1.3.4.3.2)	Analysis of the hydrologic properties of the damaged rock zone around shafts and entry drifts as preferential pathways for groundwater flow
Measured extent of the damaged rock zone surrounding shafts and drifts	Changes in geoengineering properties due to excavation (2.8.3), Opening performance stability study (8.3.2.2.3.4)	Analysis of the hydrologic properties of the damaged rock zone around shafts and entry drifts as preferential pathways for groundwater flow
Measured in situ stress in the damaged rock zone surrounding shafts and drifts	In situ stress study (8.3.2.2.3.1)	Geomechanics modeling of stress-aperture relationships

PST87-2005-8.3.3-16

8.3.3.2.2.4 Applications of results

Damaged rock zone data are required by several aspects of repository seals subsystem design and analysis. Materials selection (Section 8.3.3.4.1) will depend on the geomechanical, geochemical, thermal, and hydrologic properties of the damaged rock zone. Barrier design (Sections 8.3.3.4.1 and 8.3.3.4.2) and performance modeling (Sections 8.3.3.5.1 and 8.3.3.5.2) require input on the damaged rock zone extent, hydraulic conductivity, stress-permeability and stress-porosity relationships.

8.3.3.2.2.5 Schedule

Identification of data on the damaged rock zone that are needed by the repository seals subsystem program will be iterative and will be dependent on the overall program schedule. Refer to the sections cited in Table 8.3.3.2-2 and Section 8.5 for the schedules of activities planned to obtain data on the damaged rock zone of the repository seals subsystem.

8.3.3.3 Specific program for repository seals subsystem components and interactions testing

This section describes laboratory and field tests required to select materials, optimize design, install, and assess performance of the repository seals subsystem.

Background

Laboratory tests will investigate the physical, chemical, and hydraulic properties of the candidate barrier materials under controlled conditions. Field tests, conducted at near-surface facilities, will simulate the scale of repository openings (including boreholes) and demonstrate the emplacement methods to be used. Field tests are not necessarily intended to simulate expected repository conditions. In situ testing will be conducted to assess the performance of seals under repository conditions. These tests will be conducted following construction authorization and therefore are not within the scope of site characterization.

The regulations of 10 CFR 60.140 (NRC, 1987) require performance confirmation testing to determine, where practical, whether "natural and engineered systems and components required for repository operation, or which are designed or assumed to operate as barriers after permanent closure, are operating as intended and anticipated." This program "shall have been started during site characterization and it shall continue until permanent closure." The regulations of 10 CFR 60.142 further state that borehole and shaft barriers shall be tested during the early or developmental stages of construction and that "test sections shall be established to test the effectiveness of borehole and shaft seals before full-scale operation proceeds to seal boreholes and shafts."

Summary of program

The BWIP strategy for resolution of Issue 1.12 (see Section 8.2.2.1.12.2) and for demonstrating adequate performance of the repository seals subsystem through testing will be implemented in two stages:

- Laboratory and field testing, and modeling that uses the results of such testing, will be completed prior to application for construction authorization. Development of emplacement methods for barriers in surface or near-surface mock-ups of entry drifts and characterization of emplaced barrier materials to determine their porosity and permeability will also be completed prior to license application.
- In situ testing will be started as soon as feasible after the start of repository construction. This testing will include characterization of the emplaced barrier materials and testing to determine the leakage rate through the barrier materials and adjacent rock (McCarthy, 1987).

Results from laboratory testing will be used to identify appropriate barrier materials and configurations and to select those that perform adequately. Data from these tests will be used by repository seals subsystem designs and performance assessments.

Results of field testing will be used to evaluate the methods for emplacing barriers of the advanced conceptual design(s) and to demonstrate that the barriers can be constructed as designed. Based on the results of field testing, the license application design(s) will be modified, as appropriate, from the advanced conceptual design(s). Results from field testing will also be used in the planning of in situ tests.

The results from in situ testing will be used to confirm that seals subsystem performance during 10 to 20 yr closely approximates that predicted by computer simulation. Test results will be collected over a period longer than 10 to 20 yr to evaluate interactions between the barrier materials and the host environment. Periodic testing will be used to identify significant changes in performance. Results from in situ testing will also be used to validate computer models for assessing repository seals subsystem performance.

The specific program for repository seals subsystem components and interactions testing comprises two investigations. Section 8.3.3.3.1 identifies the studies that will provide the barrier material parameters needed to resolve Issue 1.12 (see Section 8.2.2.1.12). The results of these studies will also be used in subsequent field and in situ testing, design analysis and verification, and performance assessment. Section 8.3.3.3.2 identifies the studies for development of barrier material installation methods. The results of these studies will be used to evaluate reliability in planned emplacement methods, procedures and equipment. The results of these studies will also be used in subsequent design and in situ testing.

8.3.3.3.1 Investigation for laboratory testing of barrier materials properties and interactions

This section describes the plans for laboratory investigations of candidate barrier materials. Planned laboratory investigations comprise the activities shown as boxes in Figure 8.3.3.3-1. Activities described in other sections of the repository seals subsystem program plan or in other program plans are depicted as numbered ovals in the figure. The scope of these plans is limited to the testing of samples of candidate barrier materials fabricated in the laboratory under ambient or simulated in situ conditions. Samples generated by field testing programs will be discussed in Section 8.3.3.3.2, although the testing of such samples may be conducted in a laboratory. Current conceptual designs of repository seals subsystem barriers incorporate (1) natural geologic materials for which properties are known and published for many conditions and (2) cementitious materials for which properties under repository conditions are less well understood.

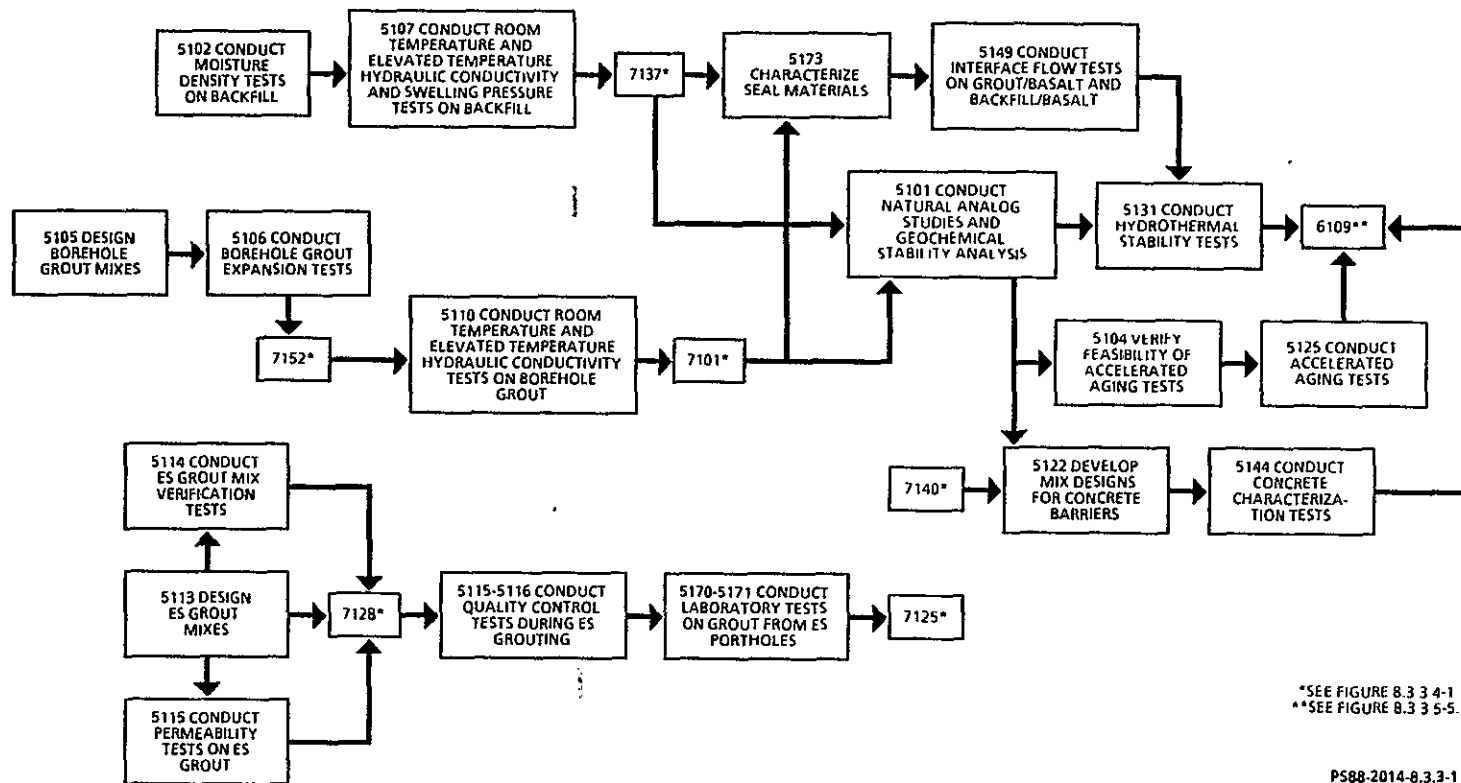


Figure 8.3.3.3-1. Laboratory testing of barrier materials, properties, and interactions.

Laboratory test data are required to supply information on barrier materials properties for advanced conceptual and license application designs. Laboratory test data are also needed to provide information on potential interactions of barrier materials with the repository host rock and groundwater for prediction of the long-term durability of proposed seals.

Several properties of candidate barrier materials and some of the environmental conditions under which they must perform their design function can be evaluated by laboratory testing. Properties and conditions that are relevant to sealing of a high-level nuclear waste repository include the following:

- Material properties--density or specific gravity, moisture-density relationships, shrinkage and swelling coefficients.
- Hydraulic properties--hydraulic conductivity, effective porosity.
- Mechanical properties--compressive, tensile, and shear strength; Young's modulus; Poisson's ratio.
- Thermal conditions--thermal conductivity, coefficient of thermal expansion, diffusivity, specific heat.
- Chemical properties--mineralogic phase stability, solubility, sorptivity, reactivity.

8.3.3.3.1.1 Purpose and objectives

Laboratory investigations of barrier materials and the interaction of these materials with components of the host environment are required to provide the data needed for the resolution of Issue 1.12, discussed in Section 8.2.2.1.12. These data will be applied to the design and analysis of repository seals, field and in situ testing, and performance assessment.

Because of facility, cost, and schedule constraints, it will be neither possible nor advisable to test all barrier components for all transient conditions that will be imposed on them during their 10,000 yr design life. Hence, data from preliminary studies, waste isolation programs in Canada and Sweden, the general literature, and sensitivity analyses (Section 8.3.3.5.1) will be used to help determine the order in which parameters are tested for each component. This information and the performance allocation process can be used to determine whether enough data already exist on some material or parameters, and if further testing is necessary. In most cases, additional testing is required to obtain the needed confidence in the data, but enough data may already exist to make preliminary material and proportion selections. Additional testing may not be necessary until the characterization of the reference materials phase.

A second purpose of laboratory testing will be to help validate (or invalidate) the predictions of sensitivity analyses and performance assessments by comparing them with the results of confirmatory laboratory

tests. A major issue that must be addressed by the repository seals subsystem program is whether barrier materials will maintain their design functions for 10,000 yr. The probability that barrier materials will retain their as-installed properties will be enhanced by choices that are chemically and physically compatible with in situ conditions. Materials stability can be investigated by thermodynamic analysis and laboratory testing under conditions that simulate accelerated aging. Such testing requires as long a time as can be made available for exposure of barrier materials to site groundwater and simulated in situ conditions. The study that addresses this concern is described in Section 8.3.3.3.1.3.1.

One objective of this investigation is to define the studies that will obtain the barrier material properties identified in Tables 8.2.2.1.12-3 through 8.2.2.1.12-5 and compile the data from these studies. A second objective of laboratory testing is to confirm or refute the adequacy of the tentatively selected materials.

8.3.3.3.1.2 Rationale

Postclosure repository barriers will not be installed until after the 50-yr waste retrievability period (unless a different time period is established by the NRC). Therefore, the principal objective of the repository seals investigations during the time preceding application for a license to receive and emplace high-level nuclear waste is to determine whether a repository in basalt can be sealed adequately in compliance with regulatory requirements. For the repository seals subsystem, this assessment will depend on the results of repository, waste package, and subsystem barrier design; performance assessment; and laboratory, field, and in situ testing. Laboratory testing of barrier materials will be performed in a manner that will be interactive with analyses of the sensitivity of barrier performance to changes in materials properties and design characteristics.

The allocation of performance goals and needed confidence to seals subsystem barriers and components (see Section 8.3.3.1.2) provides the basis for identification of the data needs for borehole, drift, and shaft sealing. The laboratory investigation of barrier materials and their interactions with the subsystem environment is related to resolution of Issue 1.12 and NRC concerns as discussed in Section 8.2.2.1.12. The selection and characterization of candidate barrier materials require prior development of selection criteria. These criteria are the requirements specific to design optimization (Section 8.3.3.4.2) and the performance goals allocated to seals subsystem components (see Section 8.2.2.1.12). Only the following general requirements for barrier materials have been identified:

- Low hydraulic conductivity.
- Ability to maintain low hydraulic conductivity at component-host rock interfaces (i.e., volume stability).
- Compatibility with the host rock and ground water.
- Long-term stability.

Effective laboratory testing requires an extensive base of information to produce data that accurately predict barrier performance. The principal information requirements for laboratory testing are as follows:

- Selection of candidate materials for testing.
- Assignment of in situ physical and chemical conditions (i.e., hydraulic gradients, temperatures, groundwater compositions, in situ stresses, etc.) that define test variables and conditions.
- Selection of barrier locations and configurations.
- Selection of barrier fabrication and emplacement methods.
- Data on host rock characteristics at barrier locations.
- Modifications of standard test methods, as appropriate, to simulate expected repository temperature and pressure conditions.

For any given laboratory test, the use of standardized test methods with specified accuracies and precisions will be required unless otherwise provided for in specific test plans.

The most significant constraints on the selection of barrier materials for testing include (1) pertinent data that are incomplete and (2) allocated performance goals and sensitivity analyses that are tentative. These constraints will necessitate an approach in which needs for additional testing will periodically be reconsidered based on updated results from design activities and performance sensitivity analyses. Similarly, needs for design modification or reanalysis of performance sensitivity may become apparent as a consequence of the laboratory testing of material properties and interactions.

An additional constraint is the questionable applicability of test results from laboratory- or bench-scale experiments to large- or full-scale barriers installed in boreholes, shafts, and entry drifts. To achieve maximum applicability, laboratory test conditions will simulate expected in situ conditions as closely as possible. Constraints imposed by time and cost of development relative to schedule and budget require that candidate barrier materials be relatively familiar (rather than exotic) through a history of use in analogous construction functions, readily available in required volumes, and easily fabricated and installed.

No alternatives to laboratory testing of properties and interactions of candidate barrier materials have been identified. Because laboratory test results are likely to have limited applicability to full-scale conditions, the repository seals subsystem program will include field testing (Section 8.3.3.3.2). However, field testing will be performed to complement laboratory testing, not as an alternative.

Laboratory test conditions will have to be based partly on assumptions of repository conditions at barrier locations until site characterization and repository design are well advanced. Hence, an option to initiating laboratory testing based on such assumptions would be to delay the testing until test conditions are well defined. This option has been rejected for two reasons. First, the basic properties of materials being considered for barrier fabrication are known from prior experience with construction of functionally similar structures. Second, long-term accelerated aging experiments, if deemed necessary, will need to be initiated early during site characterization so sufficient time is available to collect long-term test data to prepare the performance assessment and design for the application for construction authorization. Moreover, current results from performance sensitivity analyses and conceptual design work are sufficiently conservative that they provide defensible bounds for preliminary testing.

8.3.3.3.1.3 Description of studies

The laboratory investigation of barrier materials and interactions will comprise the following studies:

- Laboratory testing for selection of barrier materials (Benny, 1987c).
- Effects of elevated temperatures on physical properties of reference barrier materials (Benny, 1987a).
- Exploratory shaft grout development (Benny, 1987b).
- Long-term stability of reference barrier materials.
- Characterization of reference barrier materials.
- Interface properties of reference barrier materials.

8.3.3.3.1.3.1 Laboratory testing for selection of barrier materials

Materials currently being considered as candidates for fabricating repository barriers are composites (e.g., backfill composed of crushed basalt and bentonite). Hence, each material significant to performance must be selected and characterized, and its optimum proportion must be determined. This activity will provide data that will be used by field and in situ testing to adjust, for example, the proportions of constituents to optimize performance per unit cost. Tentative identifications and characterizations of candidate barrier materials have been made based on published technical information and early BWIP testing results. The nuclear waste isolation programs in Sweden and Canada have provided a great deal of this information. The Canadian program is considering a mixture of bentonite-granite similar to the bentonite-basalt mixture being considered by BWIP (Dixon and Gray, 1985).

This laboratory study for selecting reference barrier materials will be performed during the initial part of the site characterization period (Benny, 1987c). Reference materials selected as a result of this study will be used in subsequent tests and will help narrow the initial scope of sensitivity and design analyses.

8.3.3.3.1.3.2 Effects of elevated temperatures on physical properties of reference barrier materials

The emplaced waste is expected to generate considerable radiogenic heat. Consequently, temperatures at the repository level of the shafts are expected to begin rising within 1,000 yr with peak temperatures (approximately 83 °C) to be reached more than 10,000 yr after waste emplacement (Seitz et al., 1986). The effects these elevated temperatures will have on barrier materials will be the subject of a laboratory study during the initial part of the site characterization period (Benny, 1987a). This laboratory study is needed to help address concerns expressed by the NRC generic technical position (NRC, 1986) (Section 8.3.3.1.1). The results of the study will be used by sensitivity analyses (Section 8.3.3.5.1) and repository seals subsystem design optimization (Sections 8.3.3.4.1 and 8.3.3.4.2). If the results of the study indicate that the maximum temperatures at potential barrier locations have a negligible effect on material properties important to long-term repository seals subsystem performance, most subsequent laboratory tests will likely be performed at ambient conditions, resulting in considerable time and cost savings.

8.3.3.3.1.3.3 Characterization of reference barrier materials

Based on a limited testing matrix, an initial selection of reference materials will be made. These materials will be subjected to a complete and thorough characterization during the early part of the site characterization period. This testing program will provide the additional data necessary to gain the needed confidence in the individual parameters. In some cases the needed confidence may have already been achieved; in others it may require an extensive testing program. These tests will thus serve to confirm selection decisions made earlier. The characterization of seal materials will include additional tests of hydraulic conductivity, volume stability, swelling pressure, and density, as well as consolidation, mechanical strengths, thermal and thermomechanical properties, microcharacterization of mineralogy and structure, and interactions between seal materials. Barrier materials to be tested include bentonite-basalt mixtures, concrete, and grout.

8.3.3.3.1.3.4 Long-term stability of reference barrier materials

The long-term stability of reference barrier materials will be studied during the latter part of the site characterization period. This study will consist of several parts, each of which will address the ability of the reference barrier materials to maintain their design function for 10,000 yr.

The behavior of materials over a 10,000-yr period is uncertain, particularly in a complex environment such as a nuclear waste repository. To reduce uncertainties, analytical, experimental, and theoretical methods will be used to obtain needed assurances of long-term seals performance and materials stability. The following approaches will be used in this study.

- Examination of natural analogs, which may provide data on materials alteration and behavior over geologic periods.
- Accelerated aging tests, performed under controlled laboratory conditions that are more severe than expected in situ. These conditions, however, may help to overcome sluggish reaction kinetics. These tests may permit the long-term behavior and potential alteration of materials and fluids to be determined in relatively short test durations. The accelerated aging tests may help to determine the alteration reaction paths likely to occur in situ, the conditions under which alteration will occur and the reaction/alteration rates in candidate seal materials. If results of accelerated aging tests and long-term tests (see bullet immediately below) are consistent, the accelerated aging test approach may be validated. Accelerated aging tests enable larger data sets to be obtained in a shorter period of time than will be possible in long-term tests.
- Long-term tests designed to determine the alteration of candidate seal materials and fluids under representative fluid temperature and pressure conditions. The variability of the test conditions will be reduced relative to the seal zone conditions, thus, uncertainties in data interpretation will be reduced. However, applicability to repository sealing may also be reduced. Each of these tests may last several years and will be limited in number.
- Assessment of geochemical modeling as a means to reduce and interpret experimental data on seal/groundwater/host rock systems, examine the evolution of fluid compositions under hydrothermal conditions, and determine fluid/solid phase equilibria under hydrothermal conditions.

The materials to be included in the study will be bentonite-basalt mixtures and cementitious materials. The candidate materials for testing will be selected based on results from the exploratory shaft grout development study (Benny, 1987b) and the laboratory testing for selection of seal materials study (Benny, 1987b), and confirmed by the characterization of reference seal materials study.

8.3.3.3.1.3.5 Exploratory shaft grout development

The studies for the development of grout for the exploratory shaft will support construction of the Exploratory Shaft Facility (Benny, 1987b). Materials for the exploratory shaft liner grouts initially will be selected

based on engineering judgment. Trial batches of these materials will be made and specimens tested to determine whether the mixes meet the requirements for any of the types of grout specified in the construction specifications. Once mixes have been selected and tested, the data will be reviewed and mix designs that meet construction specifications approved. These data will supplement the data obtained from the laboratory testing for the selection of barrier materials study (Benny, 1987c).

Those grout mixes approved for use in the exploratory shaft will be further tested during construction of the shafts. Results from these tests will be used for both quality control of the batching operation and to help in understanding how laboratory-derived mix designs vary under actual field conditions.

After the shafts are constructed, grout and rock core will be removed through portholes at the repository horizon. The principal purpose of these core will be to determine the safety and feasibility of breaking-out from the shaft. These core will also yield information on the effects of placement and short-term, in situ conditions on the physical properties of the grout and interface with liner and rock (Benny, 1987b). This information will be compared to the laboratory data and the field construction data to provide some insight on the effects construction and in situ conditions may have on postclosure grout seals.

8.3.3.3.1.3.6 Interface properties of reference barrier materials

Mechanical and hydraulic properties of the barrier material-host rock interface will be tested following selection and characterization of seal materials. Properties of the interfaces between the host rock and barrier components are considered likely to be a critical element of repository seals subsystem performance (Wakeley and Roy, 1986). Specific materials interfaces that will be considered are as follows:

- Bentonite-basalt/grout.
- Bentonite-basalt/host rock.
- Bentonite-basalt/shaft liner.
- Grout/host rock.
- Grout/shaft liner.

Testing to characterize the properties of these interfaces will be guided by the results from natural analog, accelerated aging, and materials selection and characterization studies. As currently defined, testing of properties of materials interfaces will include determination of leakage rates and hydrothermal alteration.

8.3.3.3.1.4 Application of results

The results of laboratory testing for barrier materials properties and interactions will contribute to repository seals subsystem design optimization (Sections 8.3.3.4.1 and 8.3.3.4.2). These results will provide information used in (1) selecting adequate natural and cementitious barrier materials, (2) helping confirm the performance characteristics of selected barrier materials, and (3) determining fabrication and emplacement factors that can affect barriers performance. Information generated by laboratory testing of properties of barrier materials interfaces will be used to help confirm that such interfaces will not become preferential pathways for transport of radionuclides to the accessible environment.

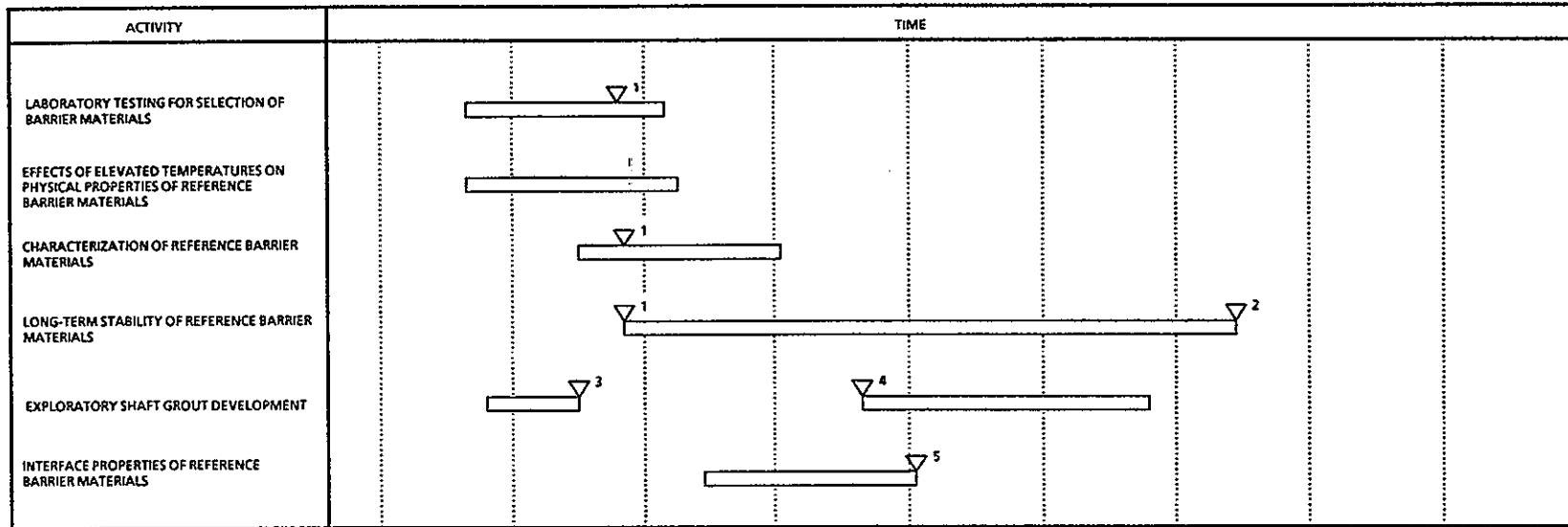
8.3.3.3.1.5 Schedule

The schedule for conducting the studies described in Section 8.3.3.1.3 is as shown in Figure 8.3.3.3-2. The schedule for completion of laboratory tests is determined by the schedule for completion of the conceptual, advanced conceptual, and license application repository designs.

8.3.3.3.2 Investigation for field testing of barrier materials properties and development of barrier emplacement methods

This section describes the plans for field investigations of candidate barrier materials and emplacement methods. Field testing is differentiated from in situ testing in that field testing will be conducted at surface facilities, with the main objective being the development of installation techniques. In situ testing will be conducted at repository depth with the main objective being installation demonstration, performance confirmation, and model validation. Because in situ testing of the repository seals subsystem elements will not be conducted until after construction authorization (see Section 8.3.3.1.1), it is not within the scope of site characterization. However, one of the activities during advanced conceptual design will be to evaluate the need for in situ tests specifically designed to measure the properties of the damaged rock zone at the seal locations (Section 8.3.3.4.1.3). The purpose of this evaluation will be to determine the need for specific tests and the schedule for these tests. Planned field testing activities are shown as boxes in Figure 8.3.3.3-3. Activities described in other sections of the repository seals subsystem program plan or in other program plans are depicted as numbered ovals in the figure.

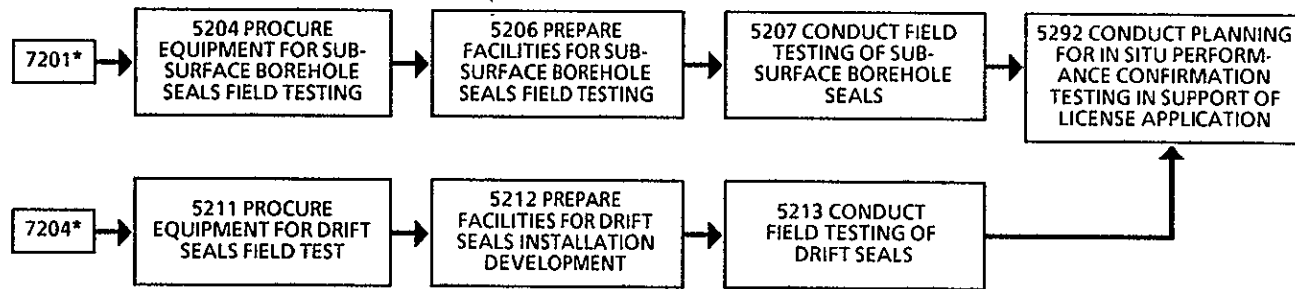
Detailed requirements for field testing of barrier components will be developed in conjunction with activities to be accomplished prior to the advanced conceptual design (Section 8.3.3.4.2). The necessity for the proposed field testing activities has been determined by the process described



PS&S-2014-4.3.3-13

- ▽ 1 SELECT CANDIDATE SEALS MATERIALS FOR SUBSEQUENT DETAILED CHARACTERIZATION
- ▽ 2 COMPLETE STUDIES OF LONG-TERM STABILITY OF SEAL MATERIALS FOR INPUT TO LICENSE APPLICATION.
- ▽ 3 SELECT CANDIDATE EXPLORATORY SHAFT GROUT MIX DESIGN.
- ▽ 4 COMPLETE INSTALLATION OF EXPLORATORY SHAFT 1 LINER AND GROUT.
- ▽ 5 COMPLETE INTERFACE FLOW TESTING AND DOCUMENTATION FOR PERFORMANCE ASSESSMENT MODEL DEVELOPMENT FOR LICENSE APPLICATION DESIGN.

Figure 8.3.3.3-2. Schedule of studies for laboratory testing.



*SEE FIGURE 8.3.3.4-3.

P588-2014-8.3.3-3

Figure 8.3.3.3-3. Field testing of barriers materials properties and demonstration of barrier emplacement methods.

in Section 8.2.2.1.12. Field demonstration tests are proposed for component emplacement methods that cannot be regarded as routine construction practice in an underground environment. Needs for full-scale testing will additionally be indicated by results of laboratory testing. Field test planning and implementation will include the following:

- Identify specific objectives for each test based on design requirements and results from previous testing.
- Define test conditions and requirements for accuracy and precision.
- Develop detailed designs and operating procedures that address test layout, instrument specification, construction methods, test procedures, data management, quality assurance, safety and environmental issues, and schedule.
- Perform pretest calculations to predict expected results (as needed for instrument range specification).
- Conduct tests and analyze data.

Methods for data recording and analysis will be defined as part of detailed test design.

8.3.3.3.2.1 Purpose and objectives

Field testing of barrier components will be required to develop the methods of barrier emplacement and confirm their adequacy as designed. Experience gained from field testing will be used to modify the design, verify parameter values used in assessing repository seals subsystem performance, and plan in situ testing.

There is no practical experience in sealing the excavated openings of a geologic repository to the performance standards of nuclear regulatory agencies. Without field testing of repository seals subsystem components, concerns that barriers cannot be constructed as designed, or that the properties of emplaced barrier materials will not be those that are predicted based on analogous uses or laboratory testing, cannot be addressed. The specific objectives of field testing include the following:

- Evaluate full-scale barrier emplacement methods and procedures.
- Evaluate and (or) develop quality assurance procedures for in situ testing and barrier construction.
- Measure properties of emplaced barrier materials for comparison with results from laboratory measurements.
- Evaluate test methods and instrumentation proposed for use by in situ testing.

To some extent, field testing may also be used to measure performance of barrier components, although this function will be more specific to in situ testing at repository depth.

8.3.3.3.2.2 Rationale

Field testing of barrier components is related to resolution of Issue 1.12 and the NRC generic technical position on borehole and shaft sealing (NRC, 1986). The overall strategy for addressing regulations and issues was discussed in Section 8.2.2.1.12.

Development of the advanced conceptual repository design will include evaluation of alternative methods for sealing subsurface openings. An objective of the design process will be to select the optimum methods for sealing these openings and to specify required installation equipment and procedures. The design process will also identify those barrier components for which field testing is required. Consequently, decisions within field testing activities will be limited to selection of the locations, scales, and instrumentation for the tests.

Barrier installation methods for boreholes originating from repository excavations will be tested at the Near-Surface Test Facility. Test boreholes will be located and sized to simulate repository construction probe holes. Locations, scales, and configurations of the boreholes have not yet been determined. Entry drift barriers will be tested in a surface facility at the Near-Surface Test Facility. Field testing at the surface is judged superior to underground field testing because a surface facility will provide better access to instrumentation at the periphery of the emplaced backfill and will have fewer scheduling and logistical constraints. The test facility will be designed to simulate the actual shape and size of repository entry drifts. A full-size facility is judged to be superior to a scaled-down facility because it will permit development of more explicit barrier emplacement and quality control procedures.

The applicability of the results from field testing will be constrained by the environment in which specific tests will be conducted. Because field test conditions will not closely simulate actual repository conditions, field testing will be used primarily to develop the methods of emplacing barriers in drifts and boreholes and to confirm their adequacy. The development of these methods is not constrained by the emplacement environment. Confirming the performance of the emplaced barrier however, is constrained by the emplacement environment and will be demonstrated during in situ testing after construction authorization. Demonstration of techniques for sealing shafts, boreholes that originate at the Earth's surface, and the damaged rock zone is rigorously constrained by the subsurface environment and, therefore, will not be part of field testing. These techniques will be demonstrated during in situ testing after construction authorization.

An alternative to field testing at the Near-Surface Test Facility would be to develop and demonstrate barrier emplacement techniques during in situ testing in the Exploratory Shaft Facility. Field testing prior to in situ

testing is preferred because of the high cost and schedule constraints associated with in situ testing and because information from field testing will be needed to effectively guide and focus in situ testing.

8.3.3.3.2.3 Description of studies

Standard methods do not exist for field testing of barrier components, and specific BWIP test methods have not yet been developed. Borehole and drift barriers will be field tested to demonstrate installation methods. A general description of these studies is given in the following sections.

8.3.3.3.2.3.1 Development of subsurface borehole barrier installation methods

Development of installation procedures for borehole barriers is required to confirm that the barriers can be emplaced as designed. This will be done in the Near-Surface Test Facility. The number of boreholes required will depend on the number of sealing methods identified in the advanced conceptual design. Five boreholes per method are initially planned. The boreholes will be sufficiently distant from one another that there will be no interference or influence among them. The boreholes will be configured to permit access to both ends of at least two boreholes. It is likely that the boreholes will be inclined. At least one borehole will be instrumented to measure the effectiveness of the emplaced barriers in restricting groundwater flow. Within the Near-Surface Test Facility, boreholes (Fig. 8.3.3.3-4) drilled from the extensometer room to the heater test room may provide the requisite conditions and geometry.

Prior to the start of the advanced conceptual design, alternative methods will be evaluated for sealing boreholes. The design will specify the installation procedures and equipment for the alternatives to be tested. Plans for testing the borehole seals will be developed based on the design specifications. Field testing of these alternatives will determine the following:

- Strengths of barrier-host rock interfaces.
- Effectiveness of the emplaced barriers in restricting groundwater flow.
- Feasibility and effectiveness of the emplacement method.
- Quality control procedures.

Results from field testing of borehole barriers will be used to specify installation procedures for subsequent in situ testing and to verify the values of parameters used for design and performance assessment.

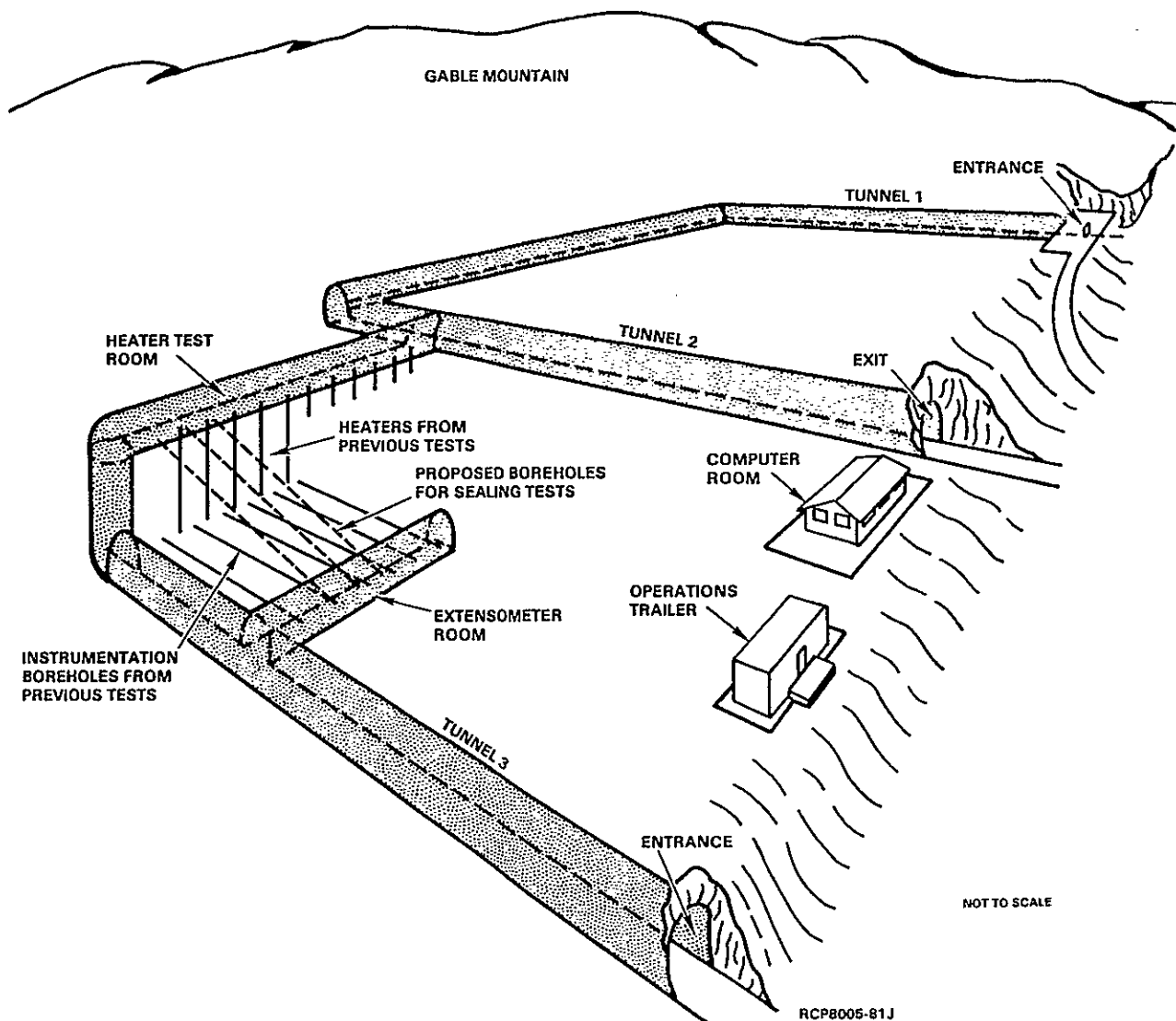


Figure 8.3.3.3-4. Boreholes drilled from the extensometer room to the heater test room in the Near-Surface Test Facility.

8.3.3.3.2.3.2 Development of drift barriers installation methods

Barriers for entry drifts will be field tested in a surface facility at the Near-Surface Test Facility that will be designed to simulate the sizes and shapes of repository entry drifts. This test facility will be constructed to provide (1) easy access to the periphery of the emplaced barrier, and (2) portals at the periphery that permit extensive sampling and instrumentation, as needed.

The objectives of field testing of entry drift barriers will be to (1) develop backfill and bulkhead emplacement technique and (2) measure properties of full-scale barriers for comparison with laboratory data. Prior to the start of advanced conceptual design, alternative methods of drift barrier emplacement will be evaluated. The design will specify the installation procedures and equipment for the alternatives to be tested. Plans for testing drift seals will be developed based on the design specifications. Field testing of these alternatives will determine the following:

- Density and moisture content (degree of saturation) of emplaced basalt-bentonite backfill.
- Strains within the backfill and at the interface between the backfill and test facility due to swelling of emplaced backfill.
- Feasibility and effectiveness of the emplacement method.
- Quality control procedures.

Results from field testing of entry drift barriers will be used to specify installation procedures for in situ testing of entry drift barriers and to verify the values of parameters used for any subsequent designs and performance assessments.

8.3.3.3.2.4 Application of results

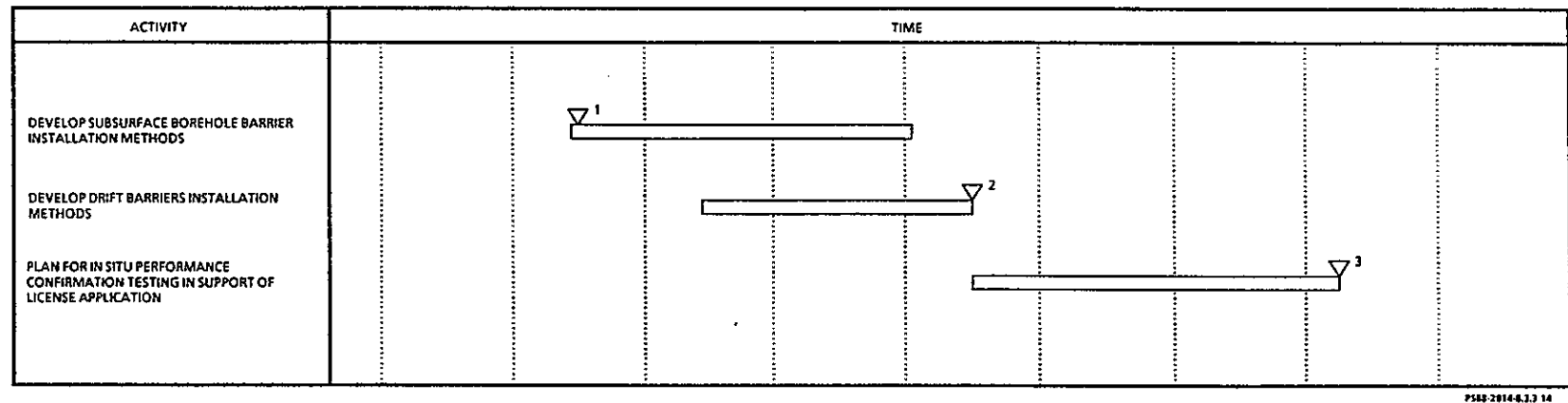
Results from field testing of borehole and drift barriers will be used to determine the feasibility of emplacing these barriers as designed. Based on this determination, the advanced conceptual designs for repository barriers will be modified, as appropriate, to obtain the license application design. Results from field testing will also be used to specify emplacement and quality control procedures for in situ testing of borehole and drift barriers.

8.3.3.3.2.5 Schedule and milestones

The schedule for field testing of repository seals subsystem components is shown in Figure 8.3.3.3-5. Preparation of study plans for specific tests will be completed at least 6 mo prior to the start of the test activity. Major completion milestones pertinent to the field testing investigation for repository seals subsystem barriers are as follow:

- Study plan for developing installation method(s) for sealing boreholes originating from the subsurface facility.
- Study plan for developing installation method(s) for sealing repository entry drifts.
- Report on recommendations of installation methods for sealing boreholes originating from the subsurface facility.
- Report on recommendations of installation methods for sealing repository entry drifts.

9 2 1 2 5 5 0 5 9 7



- ▽¹ COMPLETE STUDIES OF SUBSURFACE BOREHOLE SEALING AND DRIFT SEAL INSTALLATION, FOR FIELD TESTING.
- ▽² COMPLETE FIELD TESTING OF DRIFT AND BOREHOLE SEALS IN SUPPORT OF LICENSE APPLICATION DESIGN.
- ▽³ COMPLETE STUDIES TO SUPPORT PLANNING FOR PERFORMANCE CONFIRMATION TEST PROGRAM FOR REPOSITORY SEALS, AS INPUT TO LICENSE APPLICATION.

Figure 8.3.3.3-5. Schedule of studies and activities for field testing.

8.3.3.4 Specific program for repository seals subsystem design optimization

When the repository operational and care-taking phases are concluded, the underground facilities will be permanently closed as part of repository decommissioning. During closure, selected underground equipment will be removed; barriers will then be installed. Excavations to be closed include entry drifts, shafts, and boreholes originating from the excavations or the surface.

Background

Initial barrier materials selection was based on a materials selection process (Taylor et al., 1980, Appendix B) that included the following seven steps and related selection criteria:

1. Development of an initial list of materials--sampling of material types, compatible with the seal environment, desirable physical and chemical properties, cost and availability.
2. Preliminary screening--compatible with seal environment and documented history of survival.
3. Function classification--inhibit fluid flow, inhibit radionuclide migration, or provide structural integrity.
4. Data availability screening--large data bases.
5. Determination of material properties--permeability and thermal expansion, ion exchange and sorption, unconfined compressive strength and creep.
6. Evaluation of physical and chemical properties--dominance analysis.
7. Consideration of other factors--economic availability, compatibility with various borehole diameters (centimeters to meters), and proximal source.

The objective of the process was to identify candidate materials for use in the testing program. These materials would have a high probability for successful use in barriers and for use meeting projected NRC criteria; they also were considered suitable for use in advanced geochemical and physical testing programs. The selection approach formally and systematically examined the material selection problem using decision analysis. The selection process evaluated candidate materials in sufficient detail so that the most appropriate materials, based on current information, were selected for testing.

On the basis of the selection program and physical test results, those materials considered most suitable for consideration in future test programs and design were composites of natural materials (basalt, bentonite,

glaciofluvial sand (in cement), crushed gravel (in cement), and zeolite) and processed natural materials (portland cement Type V and grouts plus additives) (Taylor et al., 1980, p. 228). Crushed basalt-bentonite clay backfill, concrete bulkheads constructed from portland cement and crushed basalt aggregate, and portland cement grouts are the candidate materials for barrier construction. Crushed basalt will be used for structural support backfilling. Preliminary configurations and locations for the repository seals subsystem are summarized in Chapter 6 based on the SCP repository conceptual design report (KE/PB, 1987).

Summary of program

The strategy for resolving Issue 1.12 (see Section 8.2.2.1.12.2) and for addressing the NRC generic technical concerns (see Section 8.3.3.1.1) through design optimization will be implemented in an iterative manner. First, based on laboratory testing (Section 8.3.3.3.1), site investigations (Section 8.3.1), and performance sensitivity analyses (Section 8.3.3.5.1), engineering studies will be conducted to select barrier materials, locations, and configurations. Second, engineering studies will be conducted to develop installation methods for the proposed designs. Optimization of the subsystem design will then be based on further performance analysis and material and component testing. The objective of this specific program is to optimize repository seals subsystem performance and constructibility.

The specific program for repository seals subsystem design optimization comprises two investigations. Section 8.3.3.4.1 identifies the activities that will be the bases for design of barriers that comply with radionuclide isolation requirements. The results of this investigation will be used in materials testing and performance analyses. Section 8.3.3.4.2 identifies the activities associated with determining the constructibility of the proposed design. This investigation will interface closely with field testing activities in the development of installation methods.

8.3.3.4.1 Investigation to select barrier materials, configurations, and locations

This section describes the plans for selecting the materials, configurations, and locations of barriers to be placed in potential pathways to the accessible environment that are created by excavated repository openings. Planned design selection investigations comprise the activities shown as boxes in Figure 8.3.3.4-1. Activities described in other sections of the repository seals subsystem program plan (e.g., investigation of barrier materials properties and interactions) or in other program plans are depicted as numbered ovals in the figure.

The currently preferred material for postclosure sealing of repository excavations is a mixture of crushed basalt and sodium bentonite. This backfill material will be specified for advanced conceptual and license application designs in terms of the weight proportions of its solid

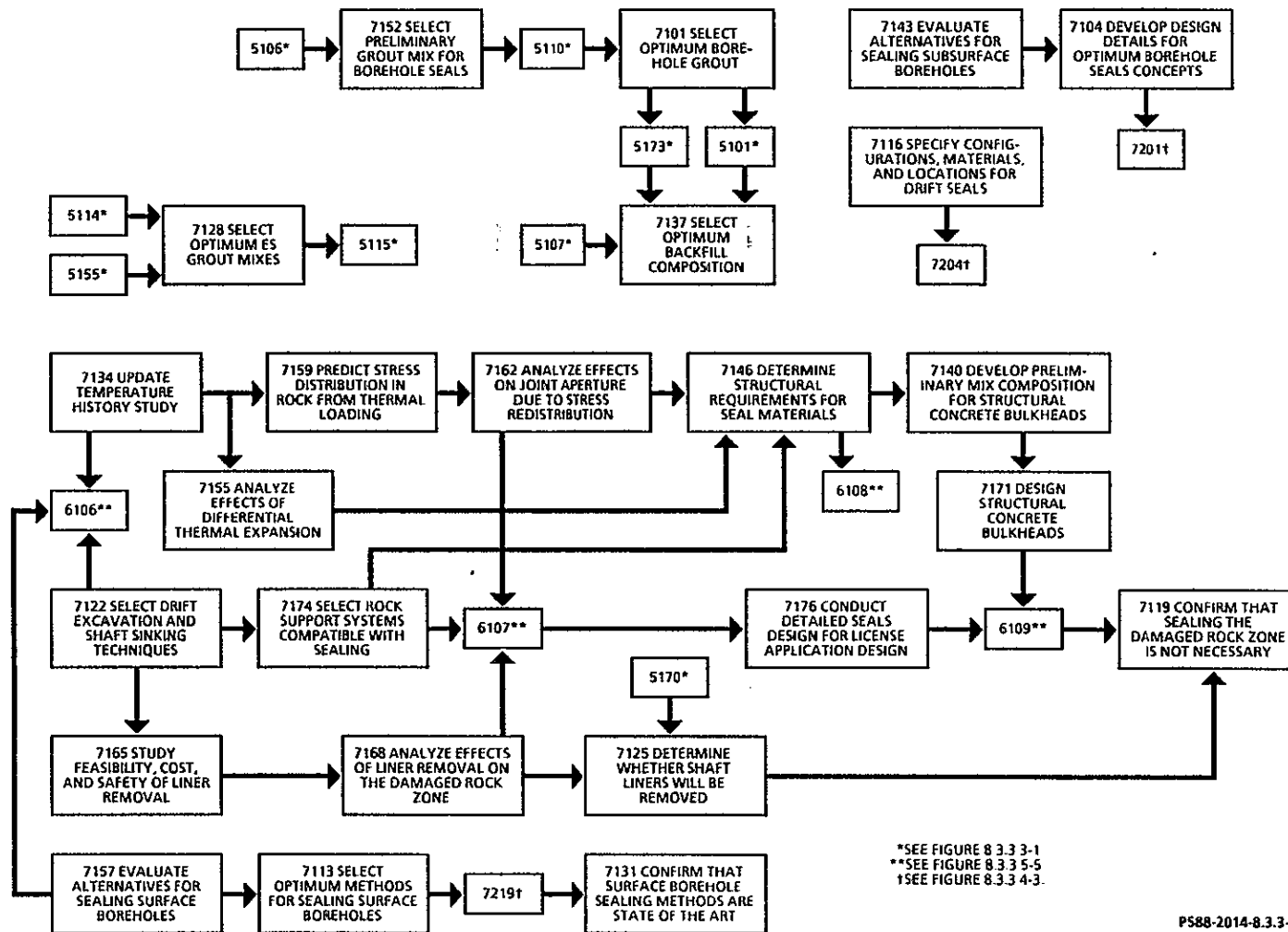


Figure 8.3.3.4-1. Selection of barrier materials, configurations, and locations.

*SEE FIGURE 8.3.3.3-1
 **SEE FIGURE 8.3.3.5-5
 †SEE FIGURE 8.3.3.4-3.

P588-2014-8.3.3-5

constituents and their size distributions, the volume proportion of entrained water, the method of mixing, and the method(s) of emplacement and compaction. The optimal percentage of bentonite in the mixture will be determined by analysis of test results, tradeoff studies, and performance sensitivity analyses. The content of bentonite specified for advanced conceptual and license application designs will be that required to reduce the hydraulic conductivity to a level that complies with the performance goal allocated to that repository seals subsystem barrier (see Table 8.2.2.1.12-4).

A second preferred material for sealing is portland cement grout and concrete. Crushed and sized basalt is the most likely aggregate for the concrete. Finely divided silica, such as silica fume or pozzolan, may be added to tie-up calcium ions within the grout and concrete by formation of calcium silicate hydrates. Various additives may be used to modify the cement hydration reaction time. A microfine cement may be used for some narrow-aperture, wall-rock fracture grouting applications. Annealed copper plugs may be used for closure of entrances to boreholes sealed with grout or crushed basalt-sodium bentonite that originate from repository excavations.

The dimensions of repository seals subsystem pathway barriers will partly be determined by the cross-sectional areas of shafts, entry drifts, boreholes, and the extent of rock damaged or disturbed by construction or geologic structural discontinuities. A second factor influencing the longitudinal dimensions of barriers will be design requirements to restrict advective and diffusive radionuclide transport.

Locations of repository seals subsystem pathway barriers will be determined by layout and design of the repository, in situ testing, and analytical studies, including performance sensitivity and design analyses. For example, identification of the nature and extent of the damaged rock zone will help determine requirements, if any, for cutoff barriers in shafts and drifts to restrict flow through the damaged rock zone bypassing the barriers.

Barriers will be installed in as yet-to-be-determined portions of shafts, entry drifts, shaft-drift intersections, and boreholes by techniques demonstrated by field and in situ testing to assure adequate performance. In addition, intersections of excavated openings with specific geologic features may require sealing. These features may include aquifers, faults, shear zones, vesicular zones, and openings excavated within structurally weak rock. Overbreak caused by blast-timing or drilling-pattern errors and wall-rock damage typical of each excavation technique may also be repaired by sealing.

8.3.3.4.1.1 Purpose and objectives

The purpose of selecting materials, configurations, and locations for sealing is to design and install barriers that comply with radionuclide isolation requirements. The objective of this investigation is to complete engineering tradeoff studies for repository seals subsystem design optimization that consider (1) dimensions and locations of barriers, (2) materials properties that influence performance, (3) barrier-wall rock interface properties, (4) amenability to quality control and verification,

(5) durability, (6) material procurement, (7) handling, preparation, and installation characteristics, and (8) cost.

8.3.3.4.1.2 Rationale

The rationale for all aspects of repository seals subsystem design is founded in Federal regulations and the BWIP strategy for resolution of Issue 1.12. Performance goals allocated to the subsystem barriers (see Section 8.3.3.1.2) that reflect the DOE issues (see Section 8.2.2) have been developed and will be used to drive the design aspects of the repository sealing program. The current set of goals for each type of subsystem barrier may be redistributed among the barrier components and parameters when site characterization and the advanced conceptual design are further advanced.

8.3.3.4.1.3 Description of activities

Activities pertaining to the selection of sealing materials, configurations, and locations are indicated in Figure 8.3.3.4-1. These activities are listed below according to the appropriate phases and responsible organizations of the design process. (Numbers in parentheses correspond to the numbered activities in Figure 8.3.3.4-1.)

- Design inputs provided by the integrating contractor include the following:
 - Select preliminary mixes for exploratory shaft grout based on analyses of geochemical stability and desired mechanical and hydraulic properties (7128).
 - Determine whether shaft liners will be removed for postclosure sealing, based on construction feasibility, cost, and performance (7125).
 - Select optimum backfill composition(s) (7137).
 - Determine whether or not sealing of the damaged rock zone is necessary (7119).
 - Select tentative grout mix (7152).
 - Select optimum borehole-sealing grout composition (7101).
- Engineering studies provided by the architect-engineer, prior to advanced conceptual design, for use in field test planning include the following:
 - Evaluate alternative methods (e.g., copper plugs, basalt-bentonite, or grout) for sealing boreholes originating from the subsurface excavations (7143).

- Provide design details and configurations for borehole barriers (7104).
- Specify configurations, materials, and locations for entry drift barriers (7116).
- Activities to be accomplished during advanced conceptual design include the following:
 - Select entry drifts excavation and repository shaft-sinking techniques that minimize damage to the host rock (7122).
 - Study and specify rock support systems in segments of entry drifts to be sealed that (1) do not use shotcrete or from which shotcrete will be removed and (2) minimize increases of hydraulic conductivity in the damaged rock zone (7174).
 - Analyze effects on joint apertures of stress redistribution from thermal loading (7162).
 - Study feasibility, cost, and safety of alternative shaft liner removal techniques (7165).
 - Analyze effects of shaft liner removal on stress redistribution and movement of jointed rock units (7168).
 - Evaluate alternative methods for sealing boreholes originating at the Earth's surface (7157).
 - Select optimum methods, materials, and configurations for sealing boreholes originating at the Earth's surface (7113).
 - Evaluate whether existing methods for sealing boreholes originating at the Earth's surface are adequate or whether development and demonstration testing will be required (7131).
 - Predict stress redistribution in host rock due to thermal loading at locations of entry drift and shaft barriers (7159).
 - Analyze effects of differential thermal expansion on barrier designs that require bonding between dissimilar materials (7155).
 - Conduct a study to predict temperature history at barrier locations (7134).
 - Evaluate the need for in situ tests specifically designed to measure the properties of the damaged rock zone at the seal locations and prepare a schedule for these tests.

- Activities to be accomplished during license application design include the following:
 - Determine structural requirements, if any, for barriers to resist movement of jointed rock units and compare with measured in situ properties (7146).
 - Design structural bulkheads and specify strength requirements for concrete (7171).
 - Conduct detailed repository seals subsystem design for final procurement and construction (7176).
 - Update survey of technical publications to develop tentative mix compositions for concrete bulkheads (7140).

8.3.3.4.1.4 Application of results

Results of design optimization activities to select barrier materials, configurations, and locations will be used in performance assessment and in laboratory, field, and in situ testing. Sensitivity analyses and assessments of repository seals subsystem performance will periodically be updated to incorporate new site characterization data and design refinements.

Selection of barrier materials, configurations, and locations will be essential to design all repository seals subsystem components and will, in some instances, affect repository layout and construction. For example, cost-benefit and performance sensitivity analyses may indicate that removal of the shaft liner and backing grout will be preferable to leaving these components in place. Then, design optimization activities will be implemented to (1) determine the feasibility, cost, and safety of removal methods; (2) analyze the effects of removal on stress redistribution and movement of jointed rock units; and (3) identify and select the materials, configurations, and locations needed to permanently seal the shafts and their damaged rock zones.

Also, based on the results of site characterization studies, it may be determined that more data are needed for repository seal subsystem design. For example, one of the activities during advanced conceptual design will be to evaluate the need for in situ tests specifically designed to measure the properties of the seals subsystem. This evaluation will be based on data compiled from other programs (see Section 8.3.3.2.2) and from performance sensitivity analyses (Section 8.3.3.5.1). The purpose of this evaluation will be to determine the need for specific tests and a schedule for these tests (i.e., pre- or post-construction authorization).

8.3.3.4.1.5 Schedule

The activities listed in Section 8.3.3.4.1.3 may be categorized as follows:

- Study borehole and drift seal materials and configurations to support field testing.
- Select seal materials and mix compositions.
- Analyze sealing alternatives and select optimum concepts and configurations (advanced conceptual design).
- Develop detailed seals design for license application (license application design.)

The schedule for completing these activities is shown in Figure 8.3.3.4-2.

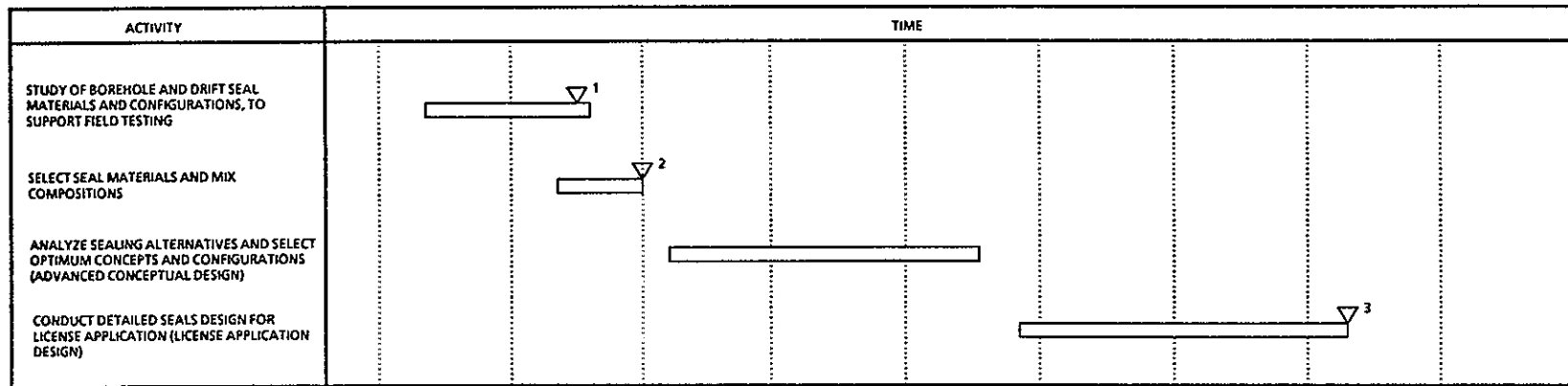
8.3.3.4.2 Investigation to develop barrier installation procedures

This section describes the plans for developing the methods for installing repository seals subsystem pathway barriers. Planned development of installation procedures comprises the activities shown as boxes in Figure 8.3.3.4-3. Activities described in other sections of the repository seals subsystem program plan or in other program plans are depicted as numbered ovals in the figure.

The constructibility of each barrier component must be evaluated and installation procedures developed. This section describes the plans for evaluating constructibility and for identifying, selecting, and developing installation methods and procedures.

8.3.3.4.2.1 Purpose and objectives

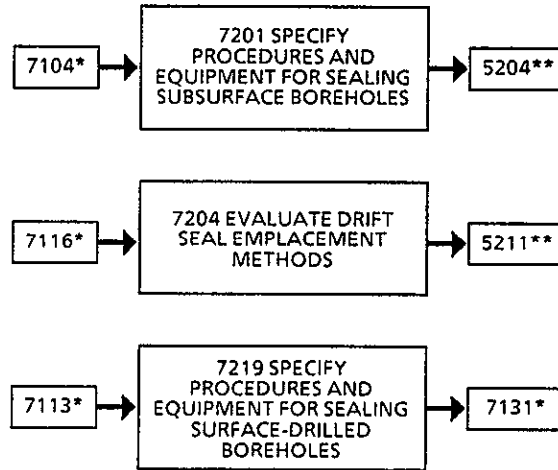
The purpose of determining constructibility of barriers as designed and developing barrier component installation procedures is to ensure that the barriers can be emplaced in compliance with design and performance requirements in a cost-effective manner. Material properties important to performance may be sensitive to techniques and equipment selected for barrier installation. Determination of these sensitivities must be made through field and in situ testing. In other words, the extent to which in situ conditions can be controlled by methods of barrier installation must be demonstrated through testing. The specific objectives of this investigation are the selection and specification of procedures and equipment for barrier installation.



PS88-2014-8.3.3-15

- ▽ 1 COMPLETE STUDIES OF SUBSURFACE BOREHOLE SEALING AND DRIFT SEAL INSTALLATION FOR FIELD TESTING.
- ▽ 2 COMPLETE PRELIMINARY SELECTION OF CANDIDATE GROUT AND BACKFILL SEAL MATERIALS, FOR SUBSEQUENT DETAILED CHARACTERIZATION.
- ▽ 3 COMPLETE SEAL DESIGN STUDIES FOR LICENSE APPLICATION

Figure 8.3.3.4-2. Schedule of activities for selection of barrier materials, configurations, and locations.



*SEE FIGURE 8.3.3.4-1.
 **SEE FIGURE 8.3.3.3-3.

PS88-2014-8.3.3-7

Figure 8.3.3.4-3. Development of barriers installation procedures.

8.3.3.4.2.2 Rationale

The basis for development of barrier installation procedures is the same as that for selection of barrier materials, configurations, and locations. The rationale is founded in the need to demonstrate that barrier emplacement methods will reduce the potential for preferential groundwater pathways and radionuclide migration through the repository seals subsystem. This potential must be reduced to achieve allocated performance goals and indications of confidence (see Section 8.2.2.1.12).

8.3.3.4.2.3 Description of activities

Activities for developing installation procedures for repository barriers were indicated in Figure 8.3.3.4-3. These activities are listed below according to the appropriate phases and responsible organizations of the design process. (Numbers in parentheses correspond to the numbered activities in Fig. 8.3.3.4-3.)

- Activities to be accomplished by the architect-engineer prior to advanced conceptual design for use in field test planning.
 - Specify procedures and equipment for sealing subsurface-drilled boreholes (7201).
 - Evaluate alternative methods of emplacing basalt-bentonite drift backfill compared to pneumatic stowing (7204).

- Activities to be accomplished during advanced conceptual design.
 - Specify equipment and procedures for sealing boreholes originating at the Earth's surface (7219).

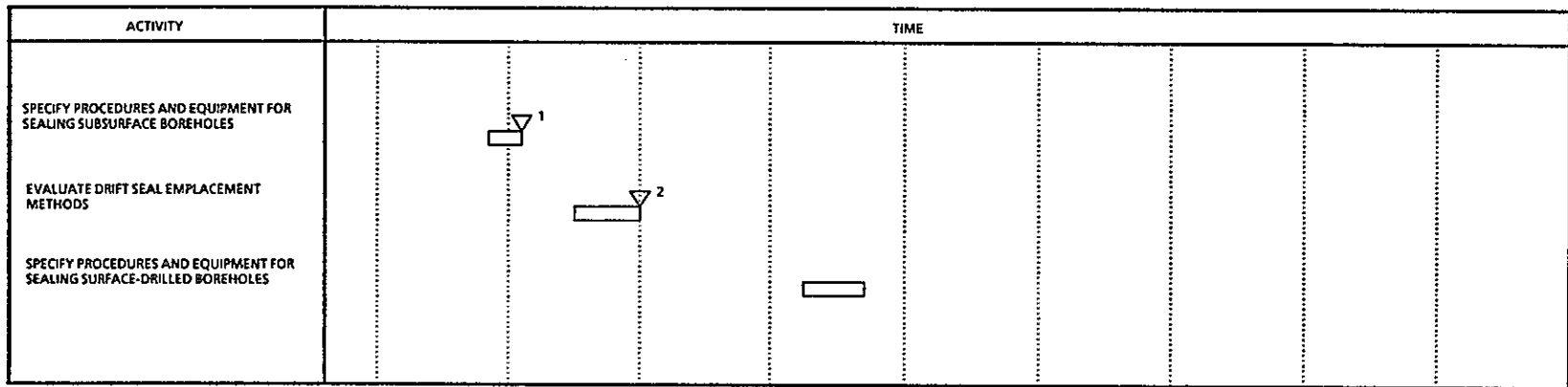
If concrete bulkheads are determined to be needed as forms for emplacement of basalt-bentonite backfill and (or) to control groundwater inflow during permanent sealing operations, activities in addition to those listed will be required.

8.3.3.4.2.4 Application of results

The results of studies for developing barrier installation procedures will be applied to advanced conceptual and license application designs. The evolution of barrier installation procedures will be closely coupled with continuing laboratory and field investigations of barrier materials and performance sensitivity analyses.

8.3.3.4.2.5 Schedule

The schedule of activities for developing barrier installation procedures is shown in Figure 8.3.3.4-4.



PS&D-2014-8.3.3-16

- ▽¹ COMPLETE STUDIES OF SUBSURFACE BOREHOLE SEAL INSTALLATION METHODS, FOR FIELD TESTING.
 ▽² COMPLETE STUDIES OF DRIFT SEAL INSTALLATION METHODS, FOR FIELD TESTING.

Figure 8.3.3.4-4. Schedule of activities for development of barrier installation procedures.

8.3.3.5 Specific program for repository seals subsystem modeling

This section describes the plans for activities to assess the postclosure performance of the repository seals subsystem. These activities will produce the computer simulations and expert judgments needed to (1) focus and guide repository seals subsystem design and installation by means of the process for allocating performance goals to repository seals subsystem pathway barriers (see Section 8.2.2.1.12) and (2) determine subsystem compliance or the inability to comply with all regulatory requirements related to repository seals subsystem performance.

Background

Two sensitivity studies (Seitz et al., 1986, 1987) of repository seals subsystem elements were completed. The performance of entry drift and borehole seals was evaluated as a function of site-specific parameters and design parameters typical of the repository underground layout. Results of these studies have contributed to the determination of parameters important to seals performance and provided estimates of the ranges of parameter values needed to meet the subsystem performance goals (see Section 8.2.2.1.12).

Studies providing initial predictions of repository seals subsystem performance were completed. The analysis of repository seals subsystem performance given in the Environmental Assessment (DOE, 1986, pp. 6-300 to 6-306) assumed that the mass fraction of radionuclides released through the repository seals subsystem would be 10% of the total mass of radionuclides released from the repository. The results of this preliminary, one-dimensional stochastic analysis suggested that the cumulative radionuclide releases from the repository seals subsystem would be less than that allowed by the EPA cumulative release limits, for a wide range of effective hydraulic conductivities along the transport pathway.

Summary of program

The specific program for repository seals subsystem modeling comprises two investigations. Section 8.3.3.5.1 describes those activities to identify the parameters whose values, if changed, would cause the largest changes in repository seals subsystem performance. The results of this investigation will be a major input for barrier design, test planning, and modeling approaches for subsequent performance assessment. Section 8.3.3.5.2 describes the activities to estimate the contribution of cumulative radionuclide releases from the repository seals subsystem to cumulative releases from the entire repository. The results of this investigation will be used to evaluate the adequacy of the repository seals subsystem design and ultimately, as input to the license application.

Performance assessment activities will guide work on the repository seals subsystem program by (1) defining the relative sensitivity of system and subsystem performance to barrier components and parameters and (2) assigning numerical performance goals. Performance goals are assigned to parameters of

subsystem pathway barriers such that, if achieved, the subsystem and system would meet their performance objectives with adequate confidence, and decisions on the need or lack of need for additional investigations and studies can be made and defended (see Section 8.2.2.1.12). By means of these evaluations, the comparative merits of alternative designs can be evaluated; and design features, site characterization information, or materials test data that may not be needed can be identified.

Because of programmatic requirements imposed by the regulations, the procedure used in assessing postclosure performance of the repository seals subsystem must be suited to analyses at the requisite spatial and temporal scales. These scales virtually preclude total reliance on laboratory and field tests to directly assess long-term waste isolation capability. The DOE plans to evaluate long-term repository performance by computer simulations and expert judgment of the dynamic processes important to release and transport of radionuclides. Computer code development and repository seals subsystem modeling are also discussed in Section 8.3.5.2.2. To evaluate overall repository performance (Section 8.3.5.2.4), the performance of each major repository subsystem (i.e., waste package, repository seals, and site) will be simulated.

Some variables in the simulation models may be expressed in terms of probability distributions to reflect uncertainties in the site characterization data, design reliability, boundary conditions, numerical computer codes, and mathematical representations. Other variables will be expressed as discrete values or as conservatively assigned bounding ranges.

The effects of barriers to radionuclide transport will be assessed by computing mass transport rates through the shafts, entry drifts, and boreholes for simulations with and without barriers of specified properties. Based on this information, materials, design configurations, and installation methods that are adequate to perform their functions of sealing shafts, entry drifts, and boreholes, will be identified.

8.3.3.5.1 Performance sensitivity investigation

This section describes the plans to investigate the performance sensitivity of candidate barrier materials, barrier designs, and component configurations. Planned sensitivity investigations comprise the activities shown in Figure 8.3.3.5-1. Activities described in other sections of the repository seals subsystem program plan or in other program plans are depicted as numbered ovals in the figure.

Identification of the parameters that significantly affect repository seals subsystem performance is an important part of barrier design optimization. When parameters that significantly affect performance are identified, design measures can be taken to maximize performance with respect to that parameter. Results of sensitivity analyses can help focus testing programs on determining values and (or) distributions of values for the

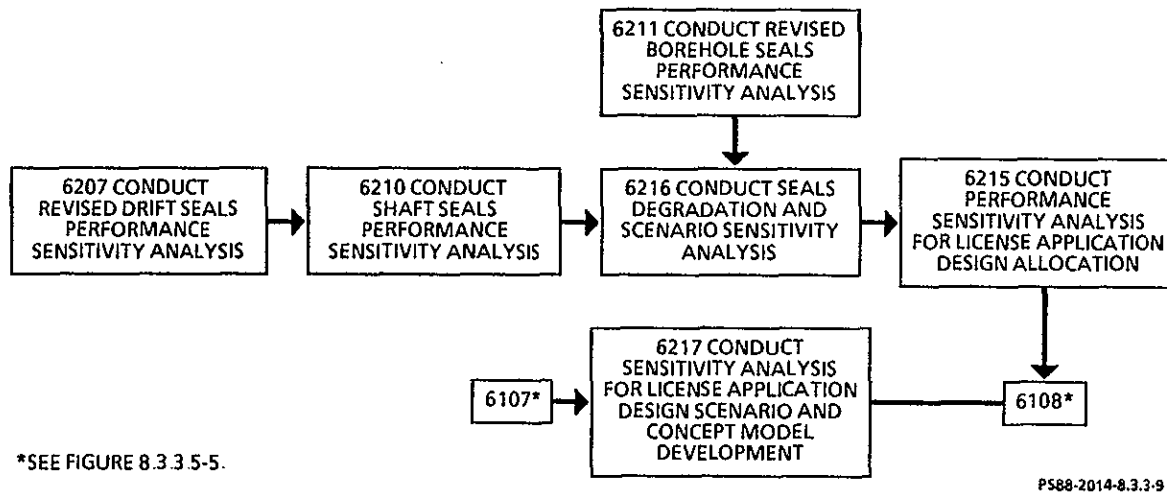


Figure 8.3.3.5-1. Performance sensitivity analyses for the repository seals subsystem.

parameters most important to performance. Proposed testing can then be eliminated or minimized for parameters not important to performance.

8.3.3.5.1.1 Purpose and objectives

The purpose of the repository seals subsystem sensitivity analyses is to identify the parameters whose values, if changed, cause the largest changes in repository seals subsystem performance. These analyses can also help determine the maximum or minimum value of a parameter that is needed to meet a performance goal allocated to a barrier component. These results provide the guidance necessary to establish performance goals for the repository seals subsystem, subsystem elements, and individual parameters that characterize these elements; and thus, sensitivity analyses are an integral part of the performance allocation process. Therefore, the results of sensitivity analyses will be a major consideration for barrier design, test planning, and modeling approaches for subsequent performance assessments.

Sensitivity analyses will provide results that directly address information needed to resolve the NRC (1986) concerns (see Section 8.3.3.1.1) regarding long-term stability of barriers and maintaining low hydraulic conductivities in the sealed area. These analyses will also be necessary to resolve Issue 1.12 (DOE, 1987). The determination of minimum or maximum parameter values necessary to satisfy a performance goal will also contribute to the process of determining credible disruptive scenarios (see Section 8.3.5.2.4.4) that relate to the repository seals subsystem. Thus, sensitivity analyses will also contribute to resolution of Issue 1.1 (see Section 8.2.2.1.1) and Issue 1.12 (see Section 8.2.2.1.12) in this respect.

8.3.3.5.1.2 Rationale

Sensitivity analyses will compare performance of specific portions of the repository seals subsystem to its allocated performance goal. This goal will typically have been assigned by means of the performance allocation process described in Section 8.2.2.1.12. The assignment is made by using results from previous sensitivity studies or, in the absence of previous studies, by engineering judgment. Thus, the approach will be iterative to provide increasingly accurate results.

Several methods can be used to estimate the sensitivity of subsystem performance to variations in given parametric values. Alternatives include engineering judgment, numerical models, analytic solutions, laboratory experiments, and testing or observations. Because of the large spatial and temporal scale imposed on predicting repository performance, laboratory experiments and testing or observations cannot exclusively be relied on to provide the required results. Analytical solutions can be found for simple transport problems, but for more complex physical systems like the repository seals subsystem, analytical solutions are not feasible. Hence, the practical alternatives are engineering judgment and numerical methods. A combination of these two will be used, with most results to be obtained using numerical methods.

Confidence in numerical modeling of a physical system is governed principally by the adequacy of the conceptual model that is expressed by the numerical model and by the quality of the data. When developing a conceptual model, the objective is to adequately describe the configurations, conditions, and processes present in the actual physical system. The complexity of this representation is constrained by the model used. Examples of repository seals subsystem conceptual models for various levels of complexity are shown in Figures 8.2.2.1.12-6 and 8.2.2.1.12-7. The conceptual model used in a given analysis is, or will be, described in the document reporting the results of that analysis. The conceptual models used in completed entry drifts and borehole analyses (Seitz et al., 1986, 1987) were simplified representations of the actual system being modeled. A two-dimensional model was used to represent a fully three-dimensional system in both analyses. Other simplifications were also necessary because of several factors. Consequently, many assumptions were made to allow modeling of the desired processes with available software. As improved software is developed, the adequacy of these assumptions will be evaluated. If the results obtained using a three-dimensional model are significantly different from the previous results, performance goals, test plans, and (or) the seals design may need to be modified (see Section 8.2.2.1.12.2).

There are many computer codes that will numerically model the physical aspects of an entity such as the repository seals subsystem. Most of these codes will simulate combinations of the following:

- Steady-state and (or) transient processes.
- One-dimensional, two-dimensional, and (or) three-dimensional systems.
- Individual and (or) coupled processes (i.e., fluid flow, heat transfer and (or) mass transport).
- Fractured and (or) equivalent porous continuum.
- Deterministic and (or) stochastic representation of subsystem behavior.

A realistic representation of the repository seals subsystem by a conceptual model may require accounting for transient, three-dimensional, coupled fluid flow, heat transfer, and mass transport in a fractured medium using one or more variables. Existing computer codes cannot model all of these processes. Hence, the current strategy for numerical simulation of repository seals subsystem performance is to use either deterministic models or simplistic, one-dimensional stochastic models that simulate the subsystem as if it were a porous continuum. Preliminary studies have indicated that the porous continuum approach can be applied to flow through the Columbia River basalts. Studies on the use of the porous continuum approach are continuing (Sections 8.3.5.4 and 8.3.5.5).

The repository seals subsystem spans large spatial dimensions, yet contains features that are relatively small, such as the annulus of rock damaged by repository excavation. These contrasts in scale require the use of fine-mesh grids with a large number of nodes. Consequently, to numerically simulate repository seals subsystem performance with existing computational equipment its representation must be extensively simplified. The degree of simplification necessary depends on the capabilities of the computer codes used for the analysis.

One simplification would be to combine adjacent components of a barrier into one component with properties that are composites of those specific to its parts. In some instances, as in a completed study that assessed the sensitivity of repository seals subsystem performance to various materials properties and configurations of entry drift barriers (Seitz et al., 1986), it will be necessary to represent each small-scale component separately. For example, Seitz et al. (1986) found that repository seals subsystem performance is sensitive to hydraulic properties assigned to the relatively thin annulus of damaged rock immediately surrounding entry drifts and shafts. This analysis was conducted using a two-dimensional model, which required several simplifying assumptions. The results of this analysis will eventually have to be confirmed with a three-dimensional model, which will involve a more complex conceptual model.

The numerical model used to conduct the initial entry drifts study (Seitz et al., 1986) is the finite difference computer code, PORFLO (Runchal et al., 1985). Brief descriptions of PORFLO and other codes currently available (or that will be available in the near future) for use in sensitivity analyses are given in Table 8.3.3.5-1. The use of PORFLO in assessing repository seals subsystem performance and in contributing to analyses of cumulative radionuclide releases from the overall repository system is shown in Figure 8.3.3.5-2. More complete descriptions of computer codes are in Sections 8.3.5.4 and 8.3.5.5.

The simplified, two-dimensional conceptual model utilized in the analysis by Seitz et al. (1986) considered one shaft roughly centered between two emplacement panels. This conceptual model required approximately 4,000 nodes to mathematically represent the subsystem. In order to represent a similar model in three dimensions, approximately 50 times more nodes (200,000 nodes) would be required. The amount of memory and computer time required to run a model of this size is beyond reasonable cost and time limits. Therefore, some enhancement to the computer code is necessary to permit a three-dimensional-model representation of the repository seals.

A proposed solution to the problem is to superimpose the finer elements, such as shafts and boreholes onto a relatively coarse mesh. This approach includes the representation of shafts or boreholes as one-dimensional line elements with a given cross-sectional area. Provisions may also be made for the line elements to represent the damaged rock surrounding an excavated opening. An attempt will be made to include such features in PORFLO and PORFLO-3D as a part of the general numerical model development and testing program (also, see Sections 8.3.5.2.2.4.2 and 8.3.5.5.1.6). Early indications suggest that this approach can be implemented in the PORFLO codes.

Table 8.3.3.5-1. Principal computer codes and variants to be used for repository seals subsystem analysis

Model and code	Process(es) modeled	Seals subsystem applications	Input parameters from field and laboratory testing ^a	Quality required for input parameters and approximate dates required ^b		
				05/87 ^c	06/89 ^c	02/94 ^c
PORFLO ^d	Two-dimensional groundwater flow, heat and radionuclide transport	Drifts and shafts barriers	<ul style="list-style-type: none"> Media densities Porosities Thermal conductivities Specific heats Dispersivities Hydraulic conductivities Specific storages Radionuclide solubilities Containment time Radionuclide release durations Radionuclide sorption coefficients Molecular diffusion coefficients 	3 2 3 3 3 2 2 3 3 3 2 3	3 1 3 3 3 1 2 2 2 2 1 1	3 1 3 3 3 1 2 1 1 1 1 1
PORFLO-3-D ^d (being developed)	Three-dimensional groundwater flow, heat and radionuclide transport	Drifts and shafts barriers	• See PORFLO			
PORMC-2-D ^d (being developed)	Two-dimensional groundwater flow, heat and radionuclide transport using distributed parameters	Drifts and shafts barriers	• See PORFLO			
CHAINT ^d	Two-dimensional, multi-component transport of chain-decay radionuclides in fractured porous rock	Borehole barriers	<ul style="list-style-type: none"> Media densities Porosities Dispersivities Radionuclide solubilities Containment time Fracture aperture Radionuclide sorption coefficients Molecule diffusion coefficients 	3 2 3 3 3 3 2 3	3 1 3 2 2 3 1 2	2 1 2 1 1 3 1 1
MAGNUM-2D ^d	Two-dimensional coupled heat transport and transient groundwater flow in fractured, porous rock	Borehole barriers	<ul style="list-style-type: none"> Media densities Porosities Thermal conductivities Specific heats Dispersivities Hydraulic conductivities Specific storages 	3 2 3 3 3 2 2	3 1 3 3 3 1 2	2 1 2 2 2 1 2

^aOther input parameters are required. However, such parameter values can be assigned independently of the findings of site-specific laboratory or field testing.

^bQuality of data is expressed in relative terms, with 1 being a higher quality than 3. Judgments of data quality that is required are subjective, but are based on apparent sensitivity of model results to parameter values.

^cDates that a specific quality of data for a specific parameter is required are based on programmatic schedules for assessing performance at low, medium, and high confidence. Schedule is subject to change.

^dSee Sections 8.3.5.4 and 8.3.5.5 for more detailed descriptions.

PST87-2005-8.3.3-20

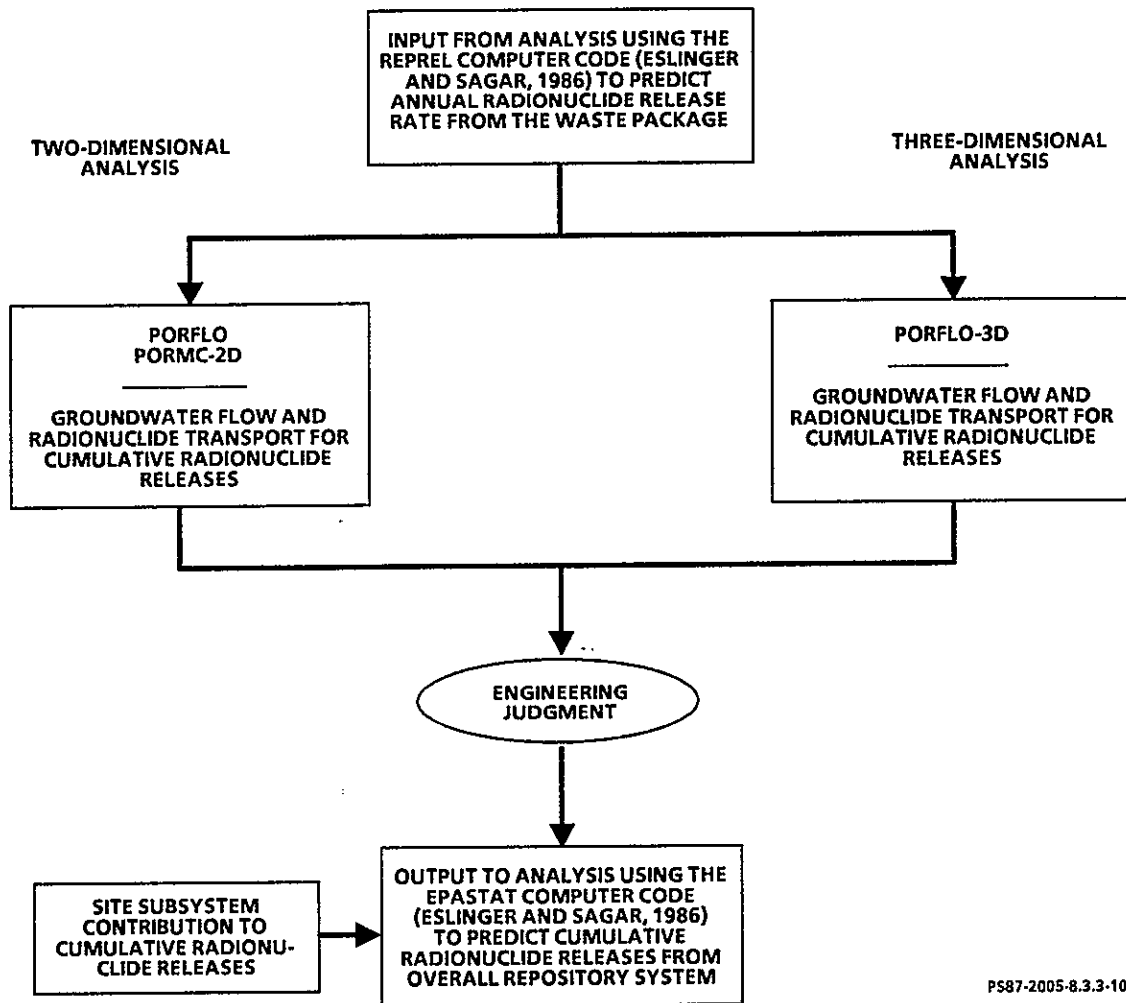


Figure 8.3.3.5-2. Use of the PORFLO computer code in assessing the repository seals subsystem performance and supporting analyses of cumulative radionuclide releases from the overall repository system.

If site characterization data indicate the presence of one or more significant zones where dense fracturing is present, the porous continuum approach may not apply to flow through such a zone. In order to address this concern, an attempt will be made to add the capability to model fracture flow through such zones to PORFLO and PORFLO-3D as part of the general numerical model development and testing program. Early indications suggest that this capability can also be added to the PORFLO codes.

The finite element computer codes MAGNUM-2D (England et al., 1985) and CHAINT (Kline et al., 1985) have also been used to assess repository seals subsystem performance. The MAGNUM-2D code and its variants (Tables 8.3.3.5-1 and 8.3.3.5-2) model groundwater flow and heat transfer. Then, the resulting flow velocities are used as input to the CHAINT code (see Table 8.3.3.5-1), which models radionuclide transport. This use of the two codes in succession (Fig. 8.3.3.5-3) is most efficient for cases in which steady-state groundwater velocities are modeled. Transient groundwater velocity can be used as inputs to CHAINT, but the computations require additional computer memory and run time. Other computer codes that may be used to simulate repository seals subsystem performance are listed in Table 8.3.3.5-2.

Another major constraint on repository seals subsystem sensitivity analyses is in the quality of model input data. The results produced by a numerical model can be no better than the data used. Currently, some of the most important site-specific parameters for radionuclide transport, such as hydraulic conductivity and coefficient of molecular diffusion, are known only with large (orders of magnitude) uncertainty. Sensitivity analyses can be useful in determining the ranges of values that are acceptable for properties of the repository seals subsystem. Hence, data uncertainty is a major reason for conducting sensitivity analyses during the initial stages of the design process (see Sections 8.3.3.4.1 and 8.3.3.4.2).

The constraints noted above for sensitivity analyses also constrain conceptual model development. The intrinsic limitations of a specific computer code must be considered when developing a conceptual model of a system whose performance is to be simulated by that code. Constraints imposed by data quality require that initial sensitivity analyses be conducted using simplified conceptual models, because the modeling results will be based on uncertain inputs. As confidence in the distributions of values of model parameters increases through site characterization, the confidence in the results produced by numerical models will also increase. Thus, more complex conceptual models may be justified as site characterization proceeds.

8.3.3.5.1.3 Description of activities

A report on the sensitivity of drift and shaft barriers performance to hydraulic properties and configurations of the damaged rock zone and drift backfill has been issued (Seitz et al., 1986). This report suggested, given

Table 8.3.3.5-2. Computer codes that may be used for ancillary analyses of the repository seals subsystem

Model and code	Process(es) modeled	Seals subsystem applications	Input parameters from field and laboratory testing ^a	Quality required for input parameters and approximate dates required ^b		
				05/87 ^c	06/89 ^c	02/94 ^c
PATH-2-D ^d (being developed)	Two-dimensional pathline plotting program	Not yet specified	See CHAINT • Output from PCM-STAT			
FECTRA ^d (being developed)	Two- or three-dimensional transport of radionuclides in porous media	Not yet specified	• Dispersivities • Molecule diffusion coefficients • Radionuclide sorption coefficients	3 3 2	3 2 1	2 1 1
MAGNUM 3-D ^d (being developed)	Three-dimensional heat transport and transient groundwater flow in fractured, porous rock	Not yet specified	• Hydraulic conductivities • Specific storages	2 2	1 2	1 2
MAGNUM 3-D-B ^d (being developed)	Three-dimensional heat transport and transient groundwater flow in fractured, porous rock, considering buoyancy effects	Not yet specified	• Output from MAGNUM 3-D-T • Hydraulic conductivities • Specific storages	2 2	2 2	2 2
MAGNUM 3-D-T ^d (being developed)	Three-dimensional transport and transient groundwater flow in fractured, porous rock by solving the heat conduction equation	Not yet specified	• Thermal conductivities • Specific heats	3 3	3 3	2 2
PATH 3-D ^d (being developed)	Three-dimensional pathline plotting program	Not yet specified	• Output from MAGNUM 3-D, including effective porosity and hydraulic conductivity			

^aOther input parameters are required. However, such parameter values can be assigned independently of the findings of site-specific laboratory or field testing.

^bQuality of data is expressed in relative terms, with 1 being higher than 3. Judgments of data quality that is required are subjective, but are based on apparent sensitivity of model results to parameter values.

^cDates that a specific quality of data for a specific parameter is required are based on programmatic schedules for assessing performance at low, medium, and high confidence. Schedule is subject to change.

^dSee Sections 8.3.5.4 and 8.3.5.5 for more detailed descriptions.

PST87-2005-8.3.3-21

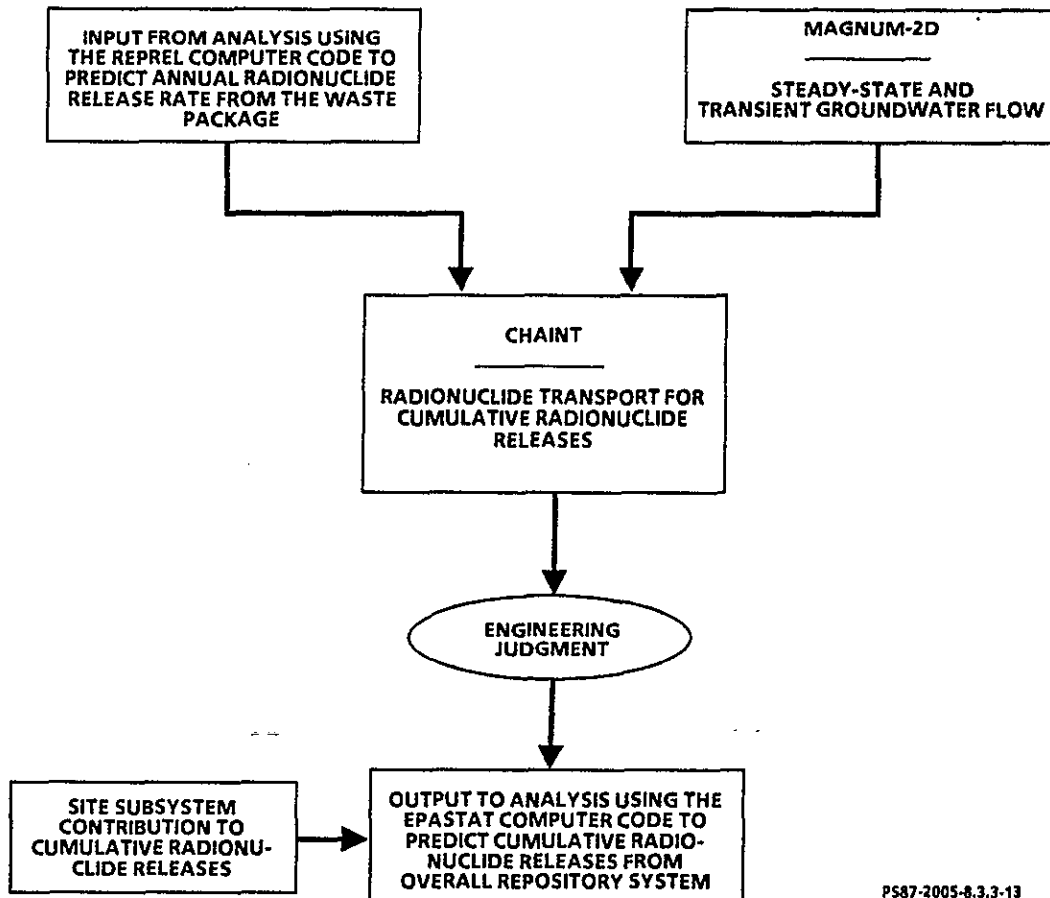


Figure 8.3.3.5-3. Use of the MAGNUM-2D and CHAINT computer codes in assessing the repository seals subsystem performance and supporting analyses of cumulative radionuclide releases from the overall repository system.

the stated assumptions, that a repository seals subsystem performance goal, permitting 1% or less of the cumulative radionuclide flux leaving waste emplacement rooms to enter the base of a shaft (see Section 8.3.3.1.2), can be attained using currently proposed barrier designs, materials, and configurations for anticipated repository conditions. This report also indicated that repository seals subsystem performance is sensitive to the hydraulic properties of the damaged rock zone and the hydraulic properties of the backfill assumed to seal the drifts. Hence, the damaged rock zone and drift backfill materials will be a major focus of repository seals subsystem testing investigations.

The sensitivity of borehole barrier performance to hydraulic properties of the damaged rock zone, hydraulic properties of barrier materials, borehole location, and borehole geometry has also been investigated (Seitz et al., 1987). This study suggested that hypothetical boreholes originating from a waste emplacement room and directed upward toward the Cohasset flow top, but not intersecting it, would likely not compromise performance of the repository. However, such boreholes intersecting the Cohasset flow top or intersecting a fracture that provides a pathway to the flow top may affect subsystem performance. Future analyses using a more refined conceptual model will be conducted to provide more definitive guidance on the necessity of sealing these boreholes.

Planned sensitivity analyses through application for construction authorization license will build on the results from completed sensitivity studies. An attempt will be made to use a three-dimensional model in these analyses. Such analyses will include the following:

- Analysis of the sensitivity of entry drift barriers performance to the repository underground layout discussed in Chapter 6.
- Analysis of the sensitivity of entry drift barriers performance, taking minimal credit for barriers in the shafts.

The objective of the layout sensitivity analysis is to determine whether proposed changes in the repository layout will significantly change the conclusions of the initial entry drift and shaft barriers sensitivity study (Seitz et al., 1986). If significant, deleterious differences in seals subsystem performance are indicated, mitigative actions may be required.

The objective of the sensitivity analysis in which minimal credit is taken for barriers in the shafts is to determine whether an extensive shaft barriers design and performance characterization program is needed. If results of the analysis indicate that repository seals subsystem performance is not highly sensitive to the hydraulic properties of candidate shaft barrier materials and configurations, installation of shaft barriers and (or) removal of segments of the shaft liners and backing grout may not be needed. If repository seals subsystem performance is sensitive to shaft barriers and damaged rock zone hydraulic properties, then results of the sensitivity analysis will be used to guide future shaft barriers modeling, design studies,

and testing. Plans for the layout and shafts sensitivity analyses are discussed in more detail in the performance analysis plan for the revised drift seal sensitivity analysis (Seitz, 1987).

Subsequent design analyses will use site characterization data specified in Sections 8.3.3.2.1 and 8.3.3.2.2 as it is acquired. Shaft sealing may be necessary based on results of sensitivity analyses of drift barrier performance that take minimal credit for shaft barrier performance. Should shaft sealing be needed, future analyses will evaluate the sensitivity of shaft seals performance to the hydraulic properties of shaft barriers and damaged rock zone sealing materials. A separate sensitivity analysis is planned to evaluate performance of seals in boreholes originating at the Earth's surface. This analysis will need to be conducted with a three-dimensional model. Additional sensitivity analyses will be conducted to determine the impact of seal materials degradation over time. The purpose of these analyses will be to estimate an acceptable range of seal material degradation (in general, increased hydraulic conductivity) to provide design guidance. Degradation that exceeds the acceptable range will be treated as a disruptive scenario.

The results of sensitivity analyses will also be used to determine minimum or maximum parameter values (bounding values) necessary to satisfy the performance goals allocated to elements of the repository seals subsystem. These values will provide guidance for the design and testing programs, as well as input to the process of determining credible disruptive scenarios.

Credible disruptive scenarios related to the repository seals will have to be identified and accounted for in performance assessments of the repository seals subsystem and the total repository system. The determination of bounding values for key parameters related to performance of the repository seals subsystem is the first step in the process of characterizing credible disruptive scenarios (see Section 8.3.5.2.4.5). Thus, these bounding values must be determined at an early stage in the design process. Previous sensitivity analyses of the repository seals subsystem have only considered limited ranges of parameter values. In some cases, bounding values could be estimated; however, the estimates were based on numerous assumptions. One objective of the revised sensitivity analysis described above will be to provide improved predictions of the bounding values for key parameters.

Sensitivity analyses will be conducted prior to the initial performance assessments of the 30% advanced conceptual design and the 30% license application design. These analyses will use the results of previous sensitivity studies and performance assessments to establish a conceptual model for performance assessments of the applicable design phase. These analyses will consider the results of previous analyses to determine how the following will be incorporated in the conceptual model for performance assessments of the applicable design:

- Disruptive scenarios.
- Seal materials degradation.

- Interdependence of borehole and shaft seal subsystems.
- Measurement of cumulative release for comparison to established goals.

The analyses described above will be performed with numerical computer codes (see Tables 8.3.3.5-1 and 8.3.3.5-2). The performance predictions from these computer simulations will generally be compared to performance goals specified through the performance allocation process (see Section 8.2.2.1.12). The specific computer code used for a given sensitivity analysis will be determined by the objectives and scope of that analysis.

8.3.3.5.1.4 Application of results

The results of repository seals subsystem sensitivity analyses will guide identification of information and information quality needs (see Section 8.2.2.1.12), future modeling efforts, test planning, and design optimization. The relationships between specific sensitivity analyses and other repository seals subsystem program investigations and studies are outlined in Figure 8.3.3.5-1. A more specific description of the applications of a given sensitivity analysis will be contained in the report for that study.

Sensitivity analyses will play an important role in the process for resolving Issue 1.12 by focusing resources on those programs most important to repository seals subsystem design and development. Using sensitivity analyses, it will be possible to determine which proposed programs are most important and should be emphasized. Sensitivity analyses will also be used to provide feedback to those determining probabilities of disruptive scenarios (see Section 8.2.2.1.8). If, as shown by sensitivity analyses, the disruptive event would have little or no impact on performance, then a lower level of confidence in the probability of that event occurring is required.

8.3.3.5.1.5 Schedule and milestones

The schedule information provided for investigations in this program includes the sequencing, interrelationships, and relative durations of the studies in the investigation. Specific durations and start/finish dates for the studies are being developed as part of ongoing planning efforts and will be provided in the SCP at the time of issuance and revised as appropriate in subsequent semiannual progress reports.

The schedule for completing sensitivity analyses is driven by testing schedules and the schedule for completing the repository conceptual, advanced conceptual, and license application designs. The schedule of activities for sensitivity analyses is given in Figure 8.3.3.5-4.

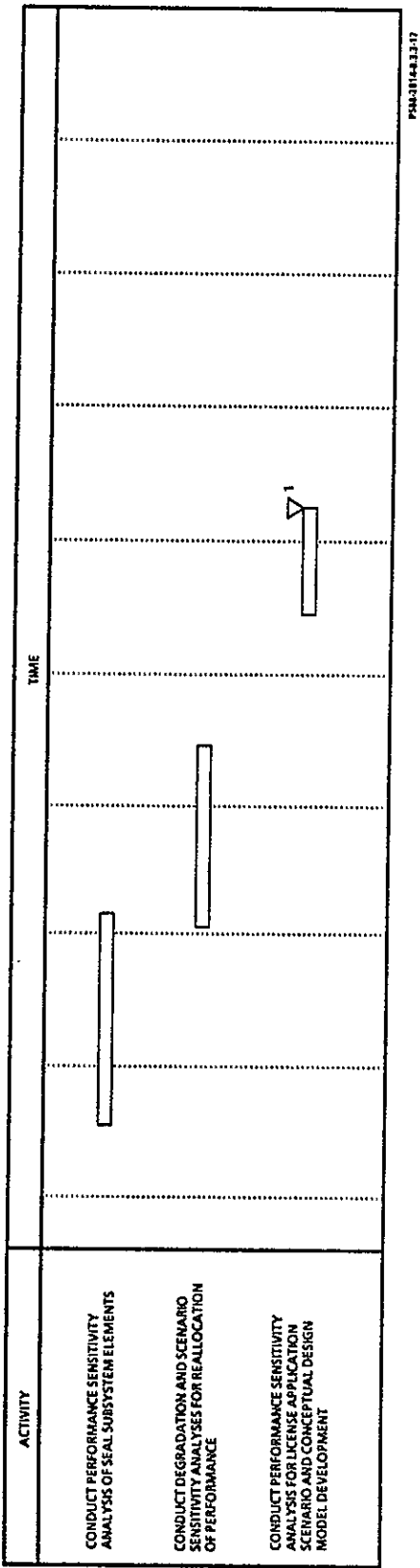


Figure 8.3.3.5-4. Schedule of activities for sensitivity analyses.

8.3.3.5.2 Performance assessment investigation

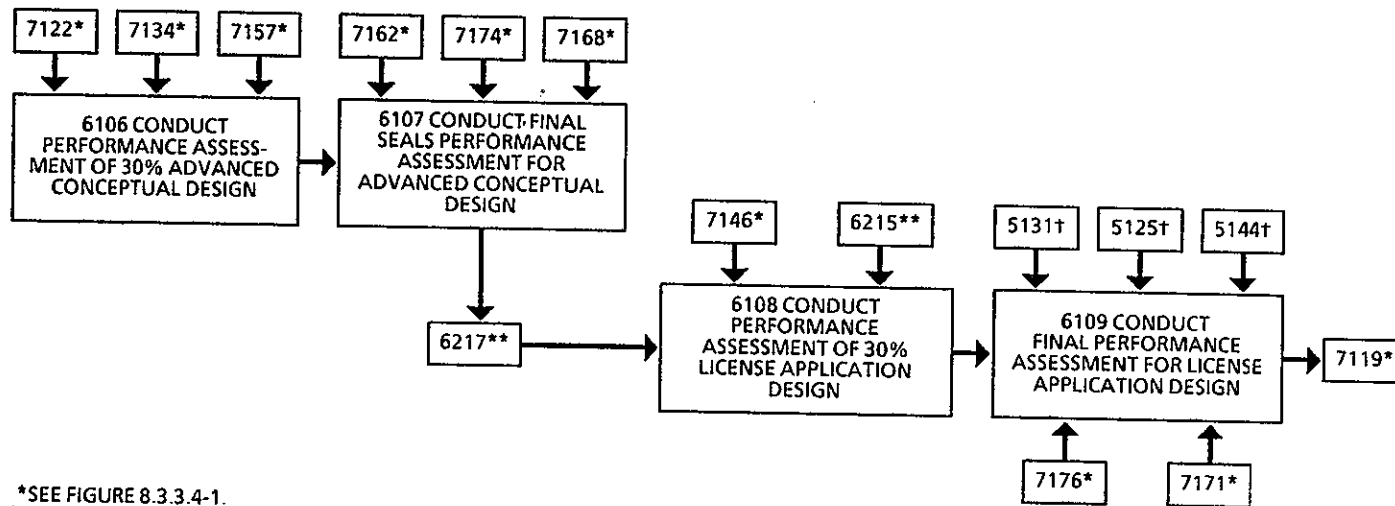
This section describes the investigation for assessing the postclosure performance of the repository seals subsystem to document a license application. Planned performance assessment activities comprise the activities shown in Figure 8.3.3.5-5. Activities described in other sections of the repository seals subsystem program plan or in other program plans are depicted as numbered ovals in the figure. These plans are also discussed in Section 8.3.5.2.2.

The relative significance of parameters for assessing repository seals subsystem performance will be determined by sensitivity analyses (see Section 8.3.3.5.1). Hence, the completion of sensitivity analyses will be an initial and integral step in assessing performance of the repository seals subsystem. Simplifications and assumptions used to derive workable conceptual models will be shown to be defensible. Whenever possible, predicted performance will be corroborated by the use of alternative mathematical models developed by a different premise or approach. Results of simulations of subsystem performance using these alternative models will be compared to extrapolated results of short-term laboratory and field tests and natural analogs, where available.

Performance assessments of preliminary advanced conceptual design phases will be made using a deterministic model. Current plans assume that performance assessments of the final advanced conceptual design and the 30% and final license application design will be made with a stochastic model in conjunction with a deterministic model. The stochastic model will be a simplified representation of subsystem behavior based on predictions of sensitivity analyses using a three-dimensional model. These assessments of repository seals subsystem performance will be made to document a construction license application using the best available estimates of parameter values, ranges, and probability distributions.

8.3.3.5.2.1 Purpose and objectives

The purpose of performance assessments is to evaluate long-term radiological effects of the emplaced waste on the accessible environment. The EPA, in 40 CFR 191.13 and Appendix A (EPA, 1986), specified numerical limits for cumulative radionuclide releases from the repository system to the accessible environment. Quantitative performance requirements for the repository seals subsystem have not been specified by either the EPA or the NRC. However, 10 CFR 60.112 and 10 CFR 60.134 (NRC, 1987) state that the repository seals subsystem shall not be a preferential pathway for radionuclide transport to the accessible environment that prevents the repository from meeting overall system postclosure performance requirements. Consequently, the specific objectives of performance assessments of the repository seals subsystem will be to estimate (a) the contribution of cumulative radionuclide releases from the repository seals subsystem to cumulative releases from the entire repository and (b) use these estimates to resolve Issue 1.12 (see Section 8.2.2.1.12) and, hence, contribute to resolution of Issue 1.1.



*SEE FIGURE 8.3.3.4-1.

**SEE FIGURE 8.3.3.5-1.

†SEE FIGURE 8.3.3.3-1.

P588-2014-8.3.3-11

Figure 8.3.3.5-5. Performance assessment activities for the repository seals subsystem.

8.3.3.5.2.2 Rationale

In general, performance assessments will be used to indicate if a proposed subsystem design is likely to comply with the performance requirements for all significant processes and events in the postclosure environment. Because the requirements are stated in terms of cumulative releases from the entire repository system to the accessible environment, predicted cumulative radionuclide releases from the repository seals subsystem will be totaled with releases from the other subsystems to estimate overall repository performance. As additional site characterization data are obtained and the repository design is refined, this process will be repeated as the need arises.

Performance assessments to be submitted in a license application must consider anticipated and unanticipated processes and events (all significant processes and events) that may impact the performance of the system (NRC, 1987, EPA 1986). Credible disruptive scenarios will be characterized for the repository seals subsystem using the process described in Section 8.3.5.2.4.5. In general, characterization of a scenario will include specification of a probability of occurrence and a change in the material properties, configuration, and(or) conditions within the model domain (see Section 8.2.2.1.12).

Relationships between performance assessment studies and other segments of the repository seals subsystem program are shown in Figure 8.3.3.5-5. Performance assessments are among the last activities of the repository seals subsystem program to be completed prior to construction license application. As each stage of the repository design process is completed, results from the assessment of the performance of that design (i.e., conceptual and advanced conceptual designs) will help guide the refinements for each subsequent design. The results of assessment of the design for construction authorization license application will be used to document compliance with Federal regulations.

Constraints on feasible alternatives for conducting performance assessments are the same as those for sensitivity (i.e., input data quality and required model simplifications). For the same reasons as stated in Section 8.3.3.5.1.2, both numerical models and engineering judgment will be used to evaluate compliance of the repository seals subsystem with applicable regulations. Because there are no quantitative performance requirements for repository seals subsystem performance, subsystem performance must be measured by alternative means. Two alternatives follow:

- Allocate a subsystem performance goal that assures that cumulative radionuclide releases through the repository seals subsystem will not cause performance of the total repository system to exceed EPA limits.
- Conduct repository seals subsystem analyses that will provide appropriate inputs to an overall repository system model that computes the system releases to the accessible environment.

Prototypic performance and sensitivity analyses have approximated repository seals subsystem behavior using a stochastic, one-dimensional conceptual model (DOE, 1987) and discrete, two-dimensional conceptual models (Seitz et al., 1986, 1987). Significant assumptions were made in these studies to simplify the true three-dimensional nature of the repository seals subsystem. These assumptions were compensated for by the deliberate introduction of conservative estimates for some parameters used to depict radionuclide transport pathways. The purpose of future analyses will be to determine whether the assumptions made in prior analyses were indeed reasonable. This evidence will be provided by analyzing the same or similar cases deterministically, in three dimensions.

In Section 8.3.3.5.1.2, the difficulties of using a three-dimensional, stochastic model for sensitivity analyses were discussed. Difficulties in performance assessment analyses are analogous. Therefore, performance assessments for the preliminary advanced conceptual design phases will be conducted in a manner similar to that of sensitivity analyses. The results of deterministic simulations will be used to estimate the expected performance for a given set of conditions. A better understanding of overall repository seals subsystem behavior will be obtained when sensitivity analyses using three-dimensional models are completed. At this time, development of a simplified, one-dimensional stochastic model will be evaluated taking into account the results of the three-dimensional model. This stochastic model would be used in conjunction with the three-dimensional model for performance assessments of the final advanced conceptual design and the 30% license application design and final license application design. The use of the two models for performance assessments should provide a more defensible estimate of cumulative radionuclide release from the repository seals subsystem.

Performance assessment must also consider the impact of disruptive scenarios. The characterization of a disruptive scenario includes defining a probability of occurrence and some specified perturbation to the nominal conditions assumed for the repository environment. The probabilistic nature of a disruptive scenario implies that a stochastic approach may be required for performance assessments. The total system analysis will consider all credible disruptive scenarios with a stochastic model. However, due to computer time constraints, the current approach is to conduct preliminary repository seals performance assessments with a deterministic model. As stated previously, performance assessment of the final advanced conceptual design, 30% license application design, and final license application design will probably be conducted with a stochastic model.

To use a deterministic model for preliminary performance assessment, individual analyses that represent each disruptive scenario related to repository seals will be conducted. The cumulative releases calculated for each analysis will then be multiplied by the probability of occurrence for the given scenario. This result will provide an estimate of performance with respect to a given scenario. If the estimated subsystem cumulative release

exceeds the performance goal for the repository seals subsystem, then the performance goal may have to be reevaluated, or the design may have to be changed to mitigate the consequences of the scenario.

The constraints imposed by data quality on sensitivity analyses (see Section 8.3.3.5.1.2) are even more limiting for performance assessment analyses because of the latter's use in license application documentation. Hence, until probability distributions for values of parameters to which performance is most sensitive are determined, preliminary assessments of performance of the conceptual design and advanced conceptual designs will be conducted using bounding parameter values judged to be conservative by engineering judgment. Data quality requirements for repository seals subsystem input parameters and the dates by which they will be required are given in Tables 8.3.3.5-1 and 8.3.3.5-2.

8.3.3.5.2.3 Description of activities

Completed studies have provided initial predictions of repository seals subsystem performance. The analysis of repository seals subsystem performance given in the Environmental Assessment (DOE, 1986) assumed that the mass fraction of radionuclides released through the repository seals subsystem would be 10% of the total mass of radionuclides released from the repository. The results of this preliminary, one-dimensional stochastic analysis using the REPSTAT computer code (Fredenburg and Sonnichsen, 1985) suggested that cumulative radionuclide releases from the repository seals subsystem would be less than that allowed by the EPA cumulative release limits, for a wide range of effective hydraulic conductivities along the transport pathway.

The entry drift barriers study (Seitz et al., 1986) discussed in Section 8.3.3.5.1.3 addressed the effects of sealing segments of the repository entry drifts with crushed basalt and bentonite. The results of that two-dimensional deterministic study suggested that the mass flux of radionuclides up the shafts, as compared to that through the site subsystem, would likely be less than 1%. This result tends to corroborate the judgment reported in the BWIP environmental assessment that the 10% fraction of total releases assumed for repository seals subsystem performance in the BWIP environmental assessment report was indeed conservative.

The borehole sealing study (Seitz et al., 1987) discussed in Section 8.3.3.5.1.3 addressed the effects of sealing boreholes originating from the subsurface facility with crushed basalt and bentonite. The results of that two-dimensional, deterministic study suggest that only boreholes that penetrate to the Cohasset flow top would need extensive sealing. Tentative performance goals (see Table 8.2.2.1.12-4) have been specified based on this analysis. Confirmation of their adequacy may require additional analyses, using a more refined conceptual model. The model used for evaluation of subsurface borehole seal performance is not adequate for evaluation of seal performance in a surface borehole. A new model will be developed to evaluate sealing performance of barriers in surface boreholes.

Performance assessments will be conducted following the completion of the 30% and 90% advanced conceptual design and license application design phases. The analyses following completion of the 90% design phases will be considered assessments of the final design. Thus, any changes between 90% and final design will have to be considered in these analyses.

Performance assessment of the 30% advanced conceptual design will be made with the computer code PORFLO-3D (Section 8.3.5.5 and Table 8.3.3.5-1). This analysis will consist of a specified set of deterministic simulations of repository performance. The set of simulations will have to adequately address all significant processes and events. The approach for this analysis will be based on the results obtained in the sensitivity analysis to be conducted at the start of advanced conceptual design (Section 8.3.3.5.1.3). An attempt will also be made to evaluate the interaction between borehole, drift, and shaft barriers, and preliminary conclusions will be made regarding the coupled responses of these barriers. A significant amount of engineering judgment will be necessary to compare the results of this analysis to the probabilistic performance goal.

Assessments of the final advanced conceptual design and the 30% and final license application designs will be made using The PORFLO-3D computer-encoded model. The model will provide predictions necessary to directly compare subsystem performance to the established goal. The approach for the performance assessments of the license application design phases will be determined in the sensitivity analysis to be conducted at the start of license application design (Section 8.3.3.5.1.3).

To assess the performance of the repository seals subsystem, annual radionuclide release rates of waste packages will be required. These rates can be obtained from a computer code such as REPREL (Section 8.3.5.4; Sagar et al., 1984). The results of the assessment of repository seals subsystem performance will be evaluated by engineering judgment to provide an appropriate input for assessment of overall system performance by a computer code such as EPASTAT (Section 8.3.5.4; Eslinger and Sagar, 1986). Figures 8.3.3.5-2 and 8.3.3.5-3 showed the sequence of analyses from the waste package to repository seals subsystem and from repository seals subsystem to the total repository system.

Because of the necessity to use engineering judgment and expert opinion to develop performance assessment models and interpret the results of analyses conducted with these models, a model validation strategy will be applied to these analyses. The main points of this strategy include the following:

- Verification and benchmark testing of computer codes.
- Formalized peer review of conceptual models, data, and assumptions used to develop models.
- Comparison of analysis results to field studies, in situ test results, and natural analogues (where available).

Additional detail on the project performance model validation strategy is presented in Section 8.3.5.3.4.

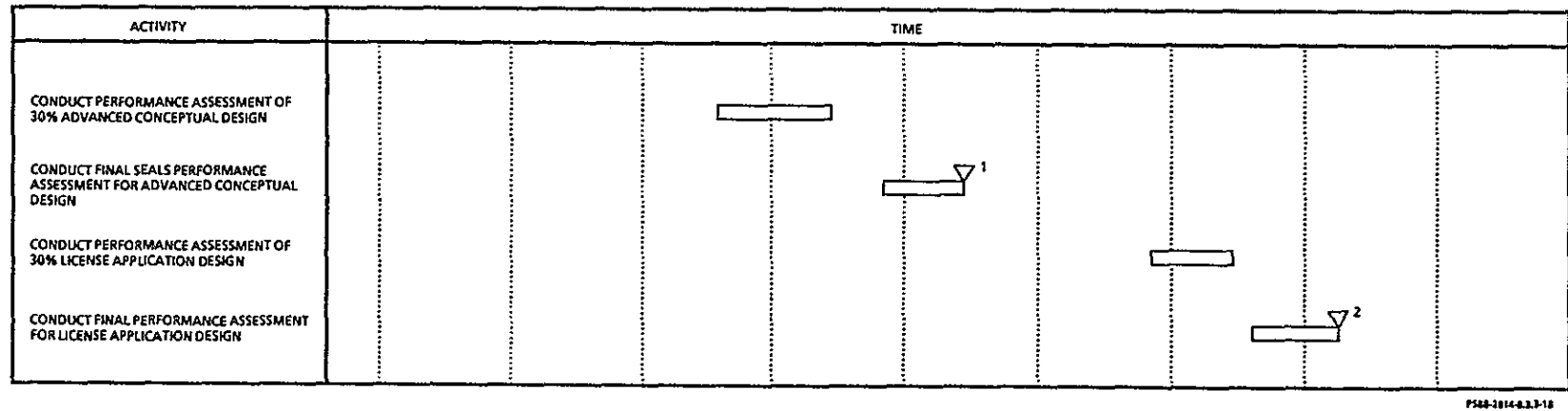
8.3.3.5.2.4 Application of results

The information obtained from the investigations described in Sections 8.3.3.2, 8.3.3.3, and 8.3.3.4 will be used to refine conceptual models and to better define values and uncertainties of parameters important to subsystem performance.

Specific inputs to performance assessments and the applications of the findings of performance assessments in resolving Issues 1.12 and 1.1 (DOE, 1987), and the NRC concerns (NRC, 1986) regarding the compatibility of seals to the host environment are shown in Figure 8.3.3.5-5. The results of assessing repository seals subsystem performance will be a basis for judging compliance with the EPA regulation limiting cumulative radionuclide releases to the accessible environment.

8.3.3.5.2.5 Schedule

The schedule for completing performance assessment studies is driven by the schedule for completing various phases of the conceptual, advanced conceptual, and license application designs. The schedule of activities for performance assessments is given in Figure 8.3.3.5-6.



- ▽¹ COMPLETE PERFORMANCE ANALYSIS OF SEALS DESIGNS FOR INPUT TO THE ADVANCED CONCEPTUAL DESIGN FINAL REPORT.
- ▽² COMPLETE PERFORMANCE ANALYSIS OF SEALS DESIGNS FOR INPUT TO THE LICENSE APPLICATION DESIGN FINAL REPORT.

Figure 8.3.3.5-6. Schedule of activities for performance assessment.

This page intentionally left blank.

9 2 1 2 5 5 5 0 6 3 4

8.3.3.6 References

- Benny, H. L., 1987a. Effects of Elevated Temperature on Physical Properties of Reference Seals Materials Study Plan, SD-BWI-SP-027, Westinghouse Hanford Company, Richland, Washington.
- Benny, H. L., 1987b. Exploratory Shaft Grout Development Study Plan, SD-BWI-SP-056, Westinghouse Hanford Company, Richland, Washington.
- Benny, H. L., 1987c. Laboratory Testing for Selection of Seals Materials Study Plan, SD-BWI-SP-026, Rockwell Hanford Operations, Richland, Washington.
- Dixon, D. A., and M. N. Gray, 1985. The Engineering Properties of Buffer Material - Research at Whiteshell Nuclear Research Establishment TR-350, Proceedings of the 19th Informational Meeting of The Nuclear Fuel Waste Management Program, Volume 1, Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, pp. 513-530.
- DOE, 1986. Environmental Assessment, Reference Repository Location, Hanford Site, Washington, DOE/RW-0070, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, Washington, D.C., pp. 6-300 to 6-306.
- DOE, 1987. Office of Geologic Repositories Issues Hierarchy for a Mined Geologic Disposal System OGR/B-10, DOE/RW-010, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, Washington, D.C.
- England, R. L., N. W. Kline, K. J. Ekblad, and R. G. Baca, 1985. MAGNUM-2D Computer Code: Users Guide, RHO-BW-CR-143 P, Rockwell Hanford Operations, Richland, Washington.
- EPA, 1986.* Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule, Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, D.C.
- Eslinger, P. W., and B. Sagar, 1986. EPASTAT: A Computer Code for Estimating Radionuclide Releases at the Accessible Environment Boundary From a Repository in Basalt, SD-BWI-TA-022, Section 8.3.5.4, Rockwell Hanford Operations, Richland, Washington.

*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Sub-part B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

- Fredenburg, E. A., and J. C. Sonnichsen, 1985. Performance Assessment in Support of Task V Engineering Studies 5, 6, 7, and 9, SD-BWI-ER-006, Rockwell Hanford Operations, Richland, Washington.
- KE/PB, 1987. Basalt Waste Isolation Project, Task V, Engineering Study No. 10, Site Characterization Plan, Conceptual Design Report, Project B-301, Vol. 1, Kaiser Engineers, Inc./Parsons Brinckerhoff Quade & Douglas, Inc., for the U.S. Department of Energy, Washington, D.C.
- Kline, N. W., R. L. England, and R. G. Baca, 1985. CHAINT Computer Code: Users Guide, RHO-BW-CR-144 P, Rockwell Hanford Operations, Richland, Washington.
- McCarthy, M. M., 1987. Subsurface Closure Engineering Plan, SD-BWI-EP-011, Rockwell Hanford Operations, Richland, Washington.
- NRC, 1986. Generic Technical Position, Borehole and Shaft Sealing of High-Level Nuclear Waste Repositories, Engineering Branch, Division of Waste Management, U.S. Nuclear Regulatory Commission, Washington, D.C.
- NRC, 1987. Disposal of High-Level Radioactive Wastes in Geologic Repositories: Technical Criteria, Title 10, Code of Federal Regulations, Part 60, Final Rule, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Runchal, A. K., B. Sagar, R. G. Baca, and N. W. Kline, 1985. PORFLO - A Continuum Model for Fluid Flow, Heat Transport in Porous Media; Model Theory, Numerical Methods, and Computational Tests, RHO-BW-CR-150 P, Rockwell Hanford Operations, Richland, Washington.
- Sagar, B., P. W. Eslinger, R. G. Baca, and R. P. Anantatmula, 1984. Probabilistic Modeling of Radionuclide Release at the Waste Package Subsystem Boundary of a Repository in Basalt, SD-BWI-TA-012, Section 8.3.5.4, Rockwell Hanford Operations, Richland, Washington.
- Seitz, R. R., J. D. Davis, and R. D. Allen, 1986. Performance Sensitivity Analysis of the Repository Seals Subsystem--Access Drift Study, SD-BWI-TI-322, Rockwell Hanford Operations, Richland, Washington.
- Seitz, R. R., 1987. Performance Analysis Plan for the Revised Drift Seal Sensitivity Analysis, SD-BWI-PA-004, Rockwell Hanford Operations, Richland, Washington.
- Seitz, R. R., M. P. Connelly, and J. D. Davis, 1987. Performance Sensitivity Analysis of the Repository Seals Subsystem--Boreholes Drilled from Repository Excavations, SD-BWI-TI-342, Rockwell Hanford Operations, Richland, Washington.

Taylor, C. T., G. J. Anttonen, J. E. O'Rourke, D. Alliot, 1980. Preliminary Geochemical and Physical Testing of Materials for Plugging of Man-Made Accesses to a Repository in Basalt, RHO-BWI-C-66, Rockwell Hanford Operations, Richland, Washington, p. 228 and Appendix B.

Wakeley, L. D., and D. M. Roy, 1986. Nature of the Interfacial Region Between Cementitious Mixtures and Rocks From the Palo During Basin and Other Seal Components, ONWI-580, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio.

9 2 1 2 5 5 5 0 6 3 7

This page intentionally left blank.

9 2 1 2 5 5 5 0 6 3 8

SITE CHARACTERIZATION PLAN

Chapter 8 - SITE CHARACTERIZATION PROGRAM

Section 8.3.4

Waste Package Program

9 2 1 2 5 5 5 0 6 3 9

THIS PAGE
INTENTIONALLY
LEFT BLANK

9 2 1 2 5 5 0 6 4 0

TABLE OF CONTENTS

	<u>Page</u>
8.3.4 Waste package program	8.3.4.1-1
8.3.4.1 Overview	8.3.4.1-1
8.3.4.1.1 Issues and issue resolution strategies guiding the program	8.3.4.1-1
8.3.4.1.2 Approach to investigations	8.3.4.1-14
8.3.4.1.3 Organization of Section 8.3.4	8.3.4.1-17
8.3.4.2 Specific program for waste package environments	8.3.4.2-1
8.3.4.2.1 Purpose and objective	8.3.4.2-3
8.3.4.2.2 Rationale	8.3.4.2-4
8.3.4.2.3 Postemplacement waste package environment investigation	8.3.4.2-4
8.3.4.2.4 Natural analogs and metallic artifacts investigation	8.3.4.2-16
8.3.4.3 Specific program to test waste package materials and interaction	8.3.4.3-1
8.3.4.3.1 Purpose and objectives	8.3.4.3-4
8.3.4.3.2 Rationale	8.3.4.3-4
8.3.4.3.3 Waste forms investigation	8.3.4.3-6
8.3.4.3.4 Container materials investigation	8.3.4.3-16
8.3.4.3.5 Packing materials investigation	8.3.4.3-35
8.3.4.3.6 Investigation of waste package radionuclide behavior	8.3.4.3-52
8.3.4.4 Specific program for waste package design development	8.3.4.4-1
8.3.4.4.1 Purpose and objectives	8.3.4.4-4
8.3.4.4.2 Rationale	8.3.4.4-5
8.3.4.4.3 Design activities investigation	8.3.4.4-7
8.3.4.4.4 Container development investigation	8.3.4.4-24
8.3.4.4.5 Packing development investigation	8.3.4.4-43
8.3.4.4.6 Qualification testing investigation	8.3.4.4-66
8.3.4.5 Specific program for waste package modeling	8.3.4.5-1
8.3.4.5.1 Purpose and objectives	8.3.4.5-2
8.3.4.5.2 Rationale	8.3.4.5-2
8.3.4.5.3 Performance sensitivity investigation	8.3.4.5-11
8.3.4.5.4 Performance and reliability investigation	8.3.4.5-19
8.3.4.5.5 Impact stress and fracture investigation	8.3.4.5-30
8.3.4.5.6 Model validation investigation	8.3.4.5-33
8.3.4.6 References	8.3.4.6-1

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.4.1-1	Waste package development process	8.3.4.1-15
8.3.4.2-1	Logic for the waste package postemplacement environment characterization investigation	8.3.4.2-9
8.3.4.2-2	Postemplacement waste package environment investigation	8.3.4.2-17
8.3.4.2-3	Strategy for the natural analogs and metallic artifacts investigation	8.3.4.2-23
8.3.4.2-4	Natural analogs and metallic artifacts investigation	8.3.4.2-29
8.3.4.3-1	Waste acceptance process for the U.S. Department of Energy	8.3.4.3-14
8.3.4.3-2	Waste forms investigation	8.3.4.3-17
8.3.4.3-3	Container materials investigation logic diagram	8.3.4.3-24
8.3.4.3-4	Container materials investigation	8.3.4.3-34
8.3.4.3-5	Packing materials investigation	8.3.4.3-53
8.3.4.3-6	Waste package radionuclide behavior investigation . . .	8.3.4.3-72
8.3.4.4-1	Waste package specific program relationships	8.3.4.4-1
8.3.4.4-2	Design activities investigation	8.3.4.4-25
8.3.4.4-3	Container development investigation	8.3.4.4-44
8.3.4.4-4	Packing development investigation methodology	8.3.4.4-49
8.3.4.4-5	Packing development investigation	8.3.4.4-65
8.3.4.4-6	Qualification testing investigation methodology diagram	8.3.4.4-70
8.3.4.4-7	Qualification testing investigation	8.3.4.4-79

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
8.3.4.5-1	Waste package performance sensitivity investigation	8.3.4.5-21
8.3.4.5-2	Waste package performance performance and reliability investigation	8.3.4.5-31
8.3.4.5-3	Impact stress/fracture investigation	8.3.4.5-34
8.3.4.5-4	Model validation investigation	8.3.4.5-39

9 2 1 2 5 5 5 0 6 4 3

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.4.1-1	Performance measures and parameters addressed by the waste package program	8.3.4.1-3
8.3.4.1-2	Summary of waste package program investigation and studies or activities	8.3.4.1-19
8.3.4.2-1	Information needs to be satisfied by the postemplacement waste package environment investigation	8.3.4.2-7
8.3.4.2-2	Summary of tests in the basalt/groundwater interactions study	8.3.4.2-12
8.3.4.2-3	Summary of tests and analyses in the geochemical environment analysis study	8.3.4.2-16
8.3.4.2-4	Information needs to be satisfied by the natural analogs and metallic artifacts investigation	8.3.4.2-20
8.3.4.2-5	Summary of tests in the waste package natural analogs study	8.3.4.2-24
8.3.4.2-6	Summary of tests in the waste package metallic artifacts study	8.3.4.2-27
8.3.4.3-1	Information needs to be satisfied by the waste forms investigation	8.3.4.3-8
8.3.4.3-2	Information needs to be satisfied by the container materials investigation	8.3.4.3-20
8.3.4.3-3	Summary of tests in general corrosion study	8.3.4.3-26
8.3.4.3-4	Summary of tests in pitting corrosion study	8.3.4.3-27
8.3.4.3-5	Summary of tests in environmentally assisted cracking study	8.3.4.3-29
8.3.4.3-6	Summary of tests in crevice corrosion study	8.3.4.3-31
8.3.4.3-7	Information needs to be satisfied by packing materials investigation	8.3.4.3-40
8.3.4.3-8	Summary of tests in packing materials chemical stability study	8.3.4.3-46

LIST OF TABLES (Continued)

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.4.3-9	Summary of tests in packing materials physical properties and processes study	8.3.4.3-49
8.3.4.3-10	Information needs to be satisfied by the waste package radionuclide behavior investigation	8.3.4.3-55
8.3.4.3-11	Summary of tests in the radionuclide solubility/sorption and speciation behavior study	8.3.4.3-60
8.3.4.3-12	Summary of tests in the waste/barrier/rock interactions: spent fuel release testing study	8.3.4.3-64
8.3.4.3-13	Summary of tests in the waste/barrier/rock interactions: borosilicate glass release testing study	8.3.4.3-68
8.3.4.4-1	Reference and options being evaluated during site characterization	8.3.4.4-6
8.3.4.4-2	Issues related to the design activities investigation	8.3.4.4-10
8.3.4.4-3	Summary of activities to be conducted by the architect-engineer during advanced conceptual design and license application design	8.3.4.4-18
8.3.4.4-4	Relevant technical concerns and corrective options versus study plan	8.3.4.4-29
8.3.4.4-5	Test methods and parameters	8.3.4.4-33
8.3.4.4-6	Technical parameters, number, and location of tests	8.3.4.4-35
8.3.4.4-7	Analysis, method of, and information produced	8.3.4.4-36
8.3.4.4-8	Major activities associated with the pressure vessel container development study	8.3.4.4-36
8.3.4.4-9	Major activities associated with the monolith container development study	8.3.4.4-39
8.3.4.4-10	Major activities associated with the nonmetallic container development study	8.3.4.4-43

LIST OF TABLES (Continued)

<u>Table</u>	<u>Title</u>	<u>Page</u>
8.3.4.4-11	Packing development investigation parameters and goals	8.3.4.4-48
8.3.4.4-12	Information needs to be satisfied by the packing development investigation	8.3.4.4-50
8.3.4.4-13	Summary of tests in packing fabrication study	8.3.4.4-54
8.3.4.4-14	Summary of tests in packing nondestructive examination study	8.3.4.4-59
8.3.4.4-15	Summary of tests in packing handling and emplacement study	8.3.4.4-61
8.3.4.4-16	Information needs to be satisfied by the qualification testing investigation	8.3.4.4-68
8.3.4.4-17	Summary of tests in container corrosion qualification study	8.3.4.4-72
8.3.4.4-18	Summary of tests in packing saturation qualification study	8.3.4.4-75
8.3.4.4-19	Summary of tests in container settlement test	8.3.4.4-77
8.3.4.5-1	Property variations for performance sensitivity investigation	8.3.4.5-14
8.3.4.5-2	Relationships between performance sensitivity investigation and other investigations	8.3.4.5-20
8.3.4.5-3	Interties between performance and reliability investigation and other investigations	8.3.4.5-30
8.3.4.5-4	Interties between impact stress and fracture investigation and other investigations	8.3.4.5-33
8.3.4.5-5	Relationships between model validation investigation and other investigations	8.3.4.5-38

8.3.4 WASTE PACKAGE PROGRAM

This section presents the purpose and rationale for the Basalt Waste Isolation Project (BWIP) waste package program and describes the studies and engineering design and analysis activities that comprise the investigations planned for the program. These investigations are grouped into the following four specific programs that make up the total waste package program:

(1) waste package environment (Section 8.3.4.2), (2) waste package materials and interaction testing (Section 8.3.4.3), (3) waste package design development (Section 8.3.4.4), and (4) waste package modeling (Section 8.3.4.5).

When completed, these programs will satisfy the information needs identified in Chapter 7 and described in the issue resolution strategies (primarily Sections 8.2.2.1.4, 8.2.2.1.5, 8.2.2.1.10, 8.2.2.2.6, and 8.2.2.4.3). The programs also will provide an assessment of whether the relevant performance and design issues (see Section 8.3.4.1.2) can be resolved. As discussed in Sections 8.1 and 8.2.1, these issues were derived from the regulatory requirements applicable to siting and licensing a geologic repository.

8.3.4.1 Overview

The purpose of the waste package program is to conduct necessary and sufficient testing, design, and modeling activities to develop a safe waste package for a nuclear waste repository in basalt. Chapter 7 described the status of the program, the current conceptual waste package design, major technical concerns, and information needs that will allow resolution of these concerns and the issues that depend on waste package performance, particularly Issues 1.4 and 1.5. Section 8.3.4 describes the plans for addressing those information needs and for developing a waste package design that will satisfy the the design and performance issues and the related regulatory requirements.

This overview subsection will (1) summarize the strategies developed in Section 8.2.2 to resolve performance issues, (2) discuss the waste package development process used to implement the strategies, and (3) describe the organization of the waste package program in terms of four specific programs and their supporting investigations, studies, or activities.

8.3.4.1.1 Issues and issue resolution strategies guiding the program

The following issues require waste-package-related performance or design information and provide the primary basis for guiding the waste package program:

- 1.4 Waste package containment.
- 1.5 Release rate.

- 1.10 Waste package (postclosure compliance with design criteria).
- 2.6 Waste package design (preclosure compliance with design criteria).
- 4.3 Waste package production.

Issue resolution strategies have been developed for each of these issues. The strategies are described in Section 8.2.2. The performance measures and parameters, tentative goals, and needed confidence that relate to meeting these goals have been extracted from the issue resolution strategies and are presented in Table 8.3.4.1-1. The waste package performance parameter goals are a result of the performance allocation process discussed in Section 8.1 and are presented with more detail as part of the issue resolution strategies in Section 8.2.2. The performance parameter goals provide targets for the program to help set priorities and guide waste package development. The needed confidence is the probability with which the value of a performance parameter must be in the favorable range for the parameter in order for the parameter to support the successful resolution of the performance or design issue.

The waste package program will generate the parameters and information needs to provide the basis for assessing whether the performance goals can be met. This assessment will be conducted as an integral part of the waste package program. The performance parameter goals and needed confidence associated with the issue resolution strategies (see Section 8.2.2) may be refined with time to reflect progress in the waste package program or changes required by the performance allocation process (Section 8.1).

The current waste package program strategy is derived primarily from the issue resolution strategies for Issues 1.4 (Section 8.2.2.1.4) and 1.5 (Section 8.2.2.1.5). These are summarized in the following paragraphs.

The waste package strategy for meeting the regulatory criteria on "substantially complete containment" and "gradual release" of radionuclides involves using successive waste package components to envelop the waste and provide a series of barriers that are chosen to limit the release of radionuclides from the waste package and engineered barriers system, respectively. The first major component will be a fully sealed container that envelops the waste form. During emplacement in the repository, the container will be placed inside an envelope of packing material composed of a tailored aggregate mixture of inorganic minerals. Depending on the emplacement configuration and specific waste package concept, there may be additional components of the waste package, and these components may contribute to performance functions of the waste package. But, in general, it will be the container and the packing that are relied upon to provide the radionuclide containment required to meet the performance criteria associated with "substantially complete containment" and "gradual release."

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 1 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Fraction of containers that do not breach for 1,000 yr (>0.8 with high confidence) (Issues 1.4 and 1.10)	Container	Provide sufficient corrosion resistance	Maximum uniform corrosion penetration in 1,000 yr	<2 cm (0.8 in.)	High
			Maximum localized corrosion penetration in 1,000 yr (assumes limited fraction of container surface area)	<10 cm (3.9 in.)	High
			Environmentally assisted cracking susceptibility	0	High
		Provide resistance to mechanical failure	Creep rupture strength for 1,000 yr	To be decided	N/A
			Buckling load	Buckling load greater than service load	High
			Threshold for crack propagation (J_{IC} or K_{IC})	$>10 \text{ MPa}\sqrt{\text{m}}$	High
	Packing	Limit mass transport	Hydraulic conductivity	$<10^{-6} \text{ cm/s}$	High
			Diffusion coefficients	$<10^{-5} \text{ cm}^2/\text{s}$	High
		Resist plastic deformation	Shear strength	30 KPa	Moderate
			Creep rate	To be decided	Moderate
<ul style="list-style-type: none"> Fraction of total inventory of radionuclides released from the engineered barriers system in any year for 1,000 yr ($<10^{-5}$ with high confidence) (Issues 1.4 and 1.10) AND Fraction of radionuclide inventory at 1,000 yr released in any one year ($<10^{-5}$ with high confidence) OR For radionuclide fraction of total inventory at 1,000 yr released in any one year ($<10^{-8}$ with high confidence) (Issues 1.5 and 1.10) 	Packing (\pm container)	Provide reducing capacity	Redox conditions	Within expected range	High
	Filler ^a	Provide support for container	Container strain	$<5\%$ diametral strain	High
	Container	Provide sufficient container failure distribution	Container failure rate under unsaturated conditions ^b	$<10/\text{yr}$	High
			• Fraction of containers that are defective	To be decided	High
			• Size of defects in container	To be decided	High
			• Depth of penetration by corrosion	To be decided	High
			Container failure rate under saturated conditions	$<10/\text{yr}$	High
			• Fraction of containers that are defective	To be decided	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 2 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
<ul style="list-style-type: none"> Fraction of total inventory of radionuclides released from the engineered barriers system in any year for 1,000 yr ($<10^{-5}$ with high confidence) (Issues 1.4 and 1.10) AND Fraction of radionuclide inventory at 1,000 yr released in any one year ($<10^{-5}$ with high confidence) (Issues 1.5 and 1.10) (cont.) 	Container (cont.)	Provide sufficient container failure distribution (cont.)	<ul style="list-style-type: none"> Size of defects in container Depth of penetration by corrosion 	To be decided To be decided	High High
	Packing (\pm container \pm filler)	Help provide and maintain reducing conditions Provide sorption capacity	Redox conditions Distribution coefficients <ul style="list-style-type: none"> Americium Plutonium Uranium Carbon Neptunium Curium Nickel Zirconium Thorium Niobium Technetium Tin Cesium Selenium Iodine 	Within expected range Within expected range Within expected range Within expected range Within expected range Within expected range Within expected range Within expected range Within expected range Within expected range To be decided Within expected range Within expected range Within expected range Within expected range	High High High High High High High High High High High High High High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 3 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence																																																
<ul style="list-style-type: none">● Fraction of total inventory of radionuclides released from the engineered barriers system in any year for 1,000 yr (<10⁻⁵ with high confidence) (Issues 1.4 and 1.10) AND● Fraction of radionuclide inventory at 1,000 yr released in any one year (<10⁻⁵ with high confidence) OR For radionuclide fraction of total inventory at 1,000 yr released in any one year (<10 ⁻⁸ with high confidence) (Issues 1.5 and 1.10) (cont.)	Packing (± container ± filler) (cont.)	Limit radionuclide solubility	Aqueous concentration for: <ul style="list-style-type: none">● Spent fuel																																																		
			<table><thead><tr><th>Element</th><th>Isotope</th><th>Mol/L</th></tr></thead><tbody><tr><td>Carbon</td><td>¹⁴C</td><td><3.5 x 10⁻⁴</td></tr><tr><td>Nickel</td><td></td><td>TBD</td></tr><tr><td>Selenium</td><td>⁷⁹Se</td><td><5.2 x 10⁻⁵</td></tr><tr><td>Zirconium</td><td>⁹³Zr</td><td><1.4 x 10⁻⁴</td></tr><tr><td>Niobium</td><td></td><td>TBD</td></tr><tr><td>Technetium</td><td>⁹⁹Tc</td><td>TBD</td></tr><tr><td>Tin</td><td>¹²⁶Sn</td><td><2.6 x 10⁻⁵</td></tr><tr><td>Cesium</td><td>¹³⁵Cs</td><td><2.3 x 10⁻⁴</td></tr><tr><td>Samarium</td><td>¹⁵¹Sm</td><td><7.0 x 10⁻⁷</td></tr><tr><td>Thorium</td><td></td><td><5.6 x 10⁻⁷</td></tr><tr><td>Uranium</td><td></td><td>1.9 x 10⁻¹</td></tr><tr><td>Plutonium</td><td></td><td>1.6 x 10⁻⁶</td></tr><tr><td>Neptunium</td><td>²³⁷Np</td><td>1.2 x 10⁻⁴</td></tr><tr><td>Americium</td><td>²⁴¹Am</td><td>4.8 x 10⁻⁹</td></tr><tr><td>Curium</td><td></td><td>1.7 x 10⁻⁷</td></tr></tbody></table>	Element	Isotope	Mol/L	Carbon	¹⁴ C	<3.5 x 10 ⁻⁴	Nickel		TBD	Selenium	⁷⁹ Se	<5.2 x 10 ⁻⁵	Zirconium	⁹³ Zr	<1.4 x 10 ⁻⁴	Niobium		TBD	Technetium	⁹⁹ Tc	TBD	Tin	¹²⁶ Sn	<2.6 x 10 ⁻⁵	Cesium	¹³⁵ Cs	<2.3 x 10 ⁻⁴	Samarium	¹⁵¹ Sm	<7.0 x 10 ⁻⁷	Thorium		<5.6 x 10 ⁻⁷	Uranium		1.9 x 10 ⁻¹	Plutonium		1.6 x 10 ⁻⁶	Neptunium	²³⁷ Np	1.2 x 10 ⁻⁴	Americium	²⁴¹ Am	4.8 x 10 ⁻⁹	Curium		1.7 x 10 ⁻⁷		High High High High High High High High High High High High High High High
			Element	Isotope	Mol/L																																																
			Carbon	¹⁴ C	<3.5 x 10 ⁻⁴																																																
			Nickel		TBD																																																
			Selenium	⁷⁹ Se	<5.2 x 10 ⁻⁵																																																
			Zirconium	⁹³ Zr	<1.4 x 10 ⁻⁴																																																
			Niobium		TBD																																																
			Technetium	⁹⁹ Tc	TBD																																																
			Tin	¹²⁶ Sn	<2.6 x 10 ⁻⁵																																																
			Cesium	¹³⁵ Cs	<2.3 x 10 ⁻⁴																																																
			Samarium	¹⁵¹ Sm	<7.0 x 10 ⁻⁷																																																
			Thorium		<5.6 x 10 ⁻⁷																																																
			Uranium		1.9 x 10 ⁻¹																																																
			Plutonium		1.6 x 10 ⁻⁶																																																
Neptunium	²³⁷ Np	1.2 x 10 ⁻⁴																																																			
Americium	²⁴¹ Am	4.8 x 10 ⁻⁹																																																			
Curium		1.7 x 10 ⁻⁷																																																			
<ul style="list-style-type: none">● High-level waste form (Defense Waste Processing Facility, West Valley Demonstration Project):																																																					
<table><thead><tr><th>Element</th><th>Isotope</th><th>Mol/L</th></tr></thead><tbody><tr><td>Zirconium</td><td>⁹³Zr</td><td><5.2 x 10⁻⁵</td></tr><tr><td>Technetium</td><td>⁹⁹Tc</td><td><1.3 x 10⁻³</td></tr><tr><td>Tin</td><td>¹²⁶Sn</td><td><2.1 x 10⁻⁵</td></tr><tr><td>Thorium</td><td>²²⁸Th</td><td><8.6 x 10⁻¹¹</td></tr><tr><td>Uranium</td><td>²³⁴U</td><td><1.5 x 10⁻¹</td></tr><tr><td>Neptunium</td><td>²³⁷Np</td><td><1.3 x 10⁻²</td></tr></tbody></table>	Element	Isotope	Mol/L	Zirconium	⁹³ Zr	<5.2 x 10 ⁻⁵	Technetium	⁹⁹ Tc	<1.3 x 10 ⁻³	Tin	¹²⁶ Sn	<2.1 x 10 ⁻⁵	Thorium	²²⁸ Th	<8.6 x 10 ⁻¹¹	Uranium	²³⁴ U	<1.5 x 10 ⁻¹	Neptunium	²³⁷ Np	<1.3 x 10 ⁻²		High High High High High High																														
Element	Isotope	Mol/L																																																			
Zirconium	⁹³ Zr	<5.2 x 10 ⁻⁵																																																			
Technetium	⁹⁹ Tc	<1.3 x 10 ⁻³																																																			
Tin	¹²⁶ Sn	<2.1 x 10 ⁻⁵																																																			
Thorium	²²⁸ Th	<8.6 x 10 ⁻¹¹																																																			
Uranium	²³⁴ U	<1.5 x 10 ⁻¹																																																			
Neptunium	²³⁷ Np	<1.3 x 10 ⁻²																																																			
<ul style="list-style-type: none">● Defense high-level waste:																																																					
<table><thead><tr><th>Element</th><th>Isotope</th><th>Mol/L</th></tr></thead><tbody><tr><td>Americium</td><td>²⁴¹Am</td><td><7.1 x 10⁻⁹</td></tr><tr><td>Nickel</td><td>⁵⁹Ni</td><td><1.6 x 10⁻⁶</td></tr><tr><td>Selenium</td><td>⁷⁹Se</td><td><2.2 x 10⁻⁷</td></tr><tr><td>Plutonium</td><td>²³⁸Pu</td><td><1.7 x 10⁻⁸</td></tr><tr><td>Curium</td><td></td><td>TBD</td></tr></tbody></table>	Element	Isotope	Mol/L	Americium	²⁴¹ Am	<7.1 x 10 ⁻⁹	Nickel	⁵⁹ Ni	<1.6 x 10 ⁻⁶	Selenium	⁷⁹ Se	<2.2 x 10 ⁻⁷	Plutonium	²³⁸ Pu	<1.7 x 10 ⁻⁸	Curium		TBD		High High High High High																																	
Element	Isotope	Mol/L																																																			
Americium	²⁴¹ Am	<7.1 x 10 ⁻⁹																																																			
Nickel	⁵⁹ Ni	<1.6 x 10 ⁻⁶																																																			
Selenium	⁷⁹ Se	<2.2 x 10 ⁻⁷																																																			
Plutonium	²³⁸ Pu	<1.7 x 10 ⁻⁸																																																			
Curium		TBD																																																			
Packing	Limit mass transport	Hydraulic conductivity	<10 ⁻⁶ cm/s	High																																																	
		Swelling pressure	<3 MPa	Moderate																																																	
		Diffusion coefficients	<10 ⁻⁵ cm ² /s	High																																																	
		Provide resistance to plastic deformation	Shear strength	30 KPa	Moderate																																																
		Creep rate	TBD	Moderate																																																	
Filler	Limit void space in container	Void fraction in container	To be decided	High																																																	

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 4 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
<ul style="list-style-type: none"> Fraction of total inventory of radionuclides released from the engineered barriers system in any year for 1,000 yr ($<10^{-5}$ with high confidence) (Issues 1.4 and 1.10) AND Fraction of radionuclide inventory at 1,000 yr released in any one year ($<10^{-5}$ with high confidence) OR For radionuclide fraction of total inventory at 1,000 yr released in any one year ($<10^{-8}$ with high confidence) (Issues 1.5 and 1.10) 	Spent fuel ^c	Limit radionuclide release rate	Radionuclide inventories for the gap and grain boundaries (these values are radionuclide-specific and depend on spent fuel irradiation history)	N/A	TBD
			Radionuclide inventory in matrix	N/A	TBD
			Ratios of specific radionuclides to uranium in the spent fuel matrix and the aqueous phase	1.0	$1.0 \pm \text{error}$ TBD
			Bounding concentrations for uranium in solution	10^{-5} to 10^{-6} M	TBD
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5	Container, filler, shell	Materials production technologies will be adequately established	Materials production methods (Issue 4.3)	Conventional processing	High
	Container, filler, packing	Component fabrication technologies will be adequately established	Materials fabrication methods (Issue 4.3)	Conventional processing (packing: dry density $>2.0 \text{ g/cm}^3$)	High
	Container, packing	Technologies will be adequately established	Handling methods/techniques (Issue 4.3)	Conventional processing	High
	Container	Closure technologies will be adequately established	Closure techniques (Issue 4.3)	Conventional techniques	High
	Container, filler, packing	Nondestructive examination technologies will be adequately established	Nondestructive examination techniques (Issue 4.3)	Conventional processing	High
	Filler	Filler installation technologies will be adequately established	Filler installation methods (Issue 4.3)	$<20\%$ total void	High
	Packing	Packing storage technology will be adequately established	Packing storage methods (Issue 4.3)	$<1\%$ moisture increase	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 5 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Waste form	Dispose of waste forms in a cost effective manner	Waste form description adequate for waste package design optimization (Issue 2.6)	Minimum waste package manufacturing, fabrication, assembly, storage, and emplacement costs	High
		Provide waste in a solid form or solidified form	Administrative controls (Issue 2.6)	Waste forms meet acceptance specifications	High
		Waste form configuration remains stable during pre-closure handling	Waste acceptance specifications performance measures (Issue 2.6)	Waste forms meet specifications	High
			Waste form strain (Issue 2.6)	<1%	High
		Limit heat output per container to prevent adverse physical effects on waste package components	Waste form temperature (Issues 1.10, 2.6)	<400 °C	High
			Filler temperature (Issues 1.10, 2.6)	TBD	High
			Container temperature (Issues 1.10, 2.6)	<430 °C	High
			Packing temperature (Issues 1.10, 2.6)	<370 °C	High
		Limit radiation per container to prevent adverse physical effects on waste package components	Degradation of container mechanical properties due to fast neutron fluence (Issues 1.10, 2.6)	Container fluence $\phi t < 10^{21} \text{ n/cm}^2$ ($E > 1.0 \text{ MeV}$)	High
		Limit heat output per container to prevent adverse chemical effects on waste package components	Waste form temperature (Issues 1.10, 2.6)	TBD	High
			Filler temperature (Issues 1.10, 2.6)	TBD	High
			Container temperature (Issues 1.10, 2.6)	TBD	High
			Packing temperature (Issues 1.10, 2.6)	<370 °C	High
		Limit radiation per container to prevent adverse chemical effects on waste package components	Enhanced container corrosion due to radiation (Issues 1.10, 2.6)	TBD α, β, γ radiation levels	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 6 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Filler	Provide adequate heat flow through waste package	Waste form temperature (Issues 1.10, 2.6)	<400 °C	High
			Packing temperature (Issues 1.10, 2.6)	<370 °C	High
		Support container to reduce strain during postulated accidents	Effective container strain during accident conditions (Issue 2.6)	TBD	High
		Limit filler interactions to prevent adverse physical effects on waste package components	Container strain (Issues 1.10, 2.6)	<5% strain	High
			Waste form strain due to filler interactions (Issues 1.10, 2.6)	<1%	High
		Limit filler interactions to prevent adverse chemical effects on waste package components	Internal container corrosion due to filler interactions (Issues 1.10, 2.6)	No significant loss of wall	High
			Waste form corrosion due to solid state reaction with filler (Issues 1.10, 2.6)	No significant loss of cladding wall	High
			Waste form corrosion due to gaseous filler reaction products (Issues 1.10, 2.6)	No significant loss of cladding wall	High
			Loss of cladding mechanical integrity due to chemical interactions with filler constituents (Issues 1.10, 2.6)	No cladding delamination	High
	Container	Prevent release of radionuclides due to undetected defects	Preclosure release of radionuclides as a result of undetected defects (Issue 2.6)	Release less than 10 CFR 20.105 (NRC, 1987b) limits	High
		Container will withstand all projected handling loads during assembly, storage, transport (including accidents), emplacement, and retrieval operations	Handling and accident induced container strain (Issue 2.6)	Less than failure strain	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 7 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Container (cont.)	Container will maintain integrity against all mechanical loads during the pre-closure period	Container strain (Issue 2.6)	Less than failure strain	High
	Filler	Provide adequate heat flow through waste package	Maximum packing temperature (Issues 1.10, 2.6)	<370 °C	High
		Reduce free volume in container for criticality control of spent fuel	Effective multiplication coefficient	$k_{eff} + 3\sigma < 0.95$	High
	Container	Limit container interactions to prevent adverse physical effects on the waste package components	Altered ground-water flow rate through packing due to interaction with container corrosion products (Issues 1.10, 2.6)	Maintain mass transport to diffusional process	High
			Altered packing mechanical properties due to interaction with container corrosion products	No significant change	High
		Limit container interaction with waste form to prevent adverse chemical effects on the waste package components	Waste form corrosion due to interaction with container material or corrosion products (Issue 2.6)	No significant loss of cladding wall	High
			Altered packing physical properties due to interaction with the container (Issue 1.10)	No significant change	High
		Limit container interaction with corrosion products to prevent adverse chemical effects on the waste package components	Altered container material properties due to interaction with corrosion products (Issue 1.10)	No significant change	High
		Limit container interaction with packing to prevent adverse chemical effects on the waste package components	Altered packing oxygen consumption due to interaction with container corrosion products (Issue 1.10)	No significant adverse change	High
			Altered packing sorptive capacity due to interaction with container corrosion products (Issue 1.10)	No significant change	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 8 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Packing	Provide adequate heat flow through the waste package	Shell temperature (Issues 1.10, 2.6)	TBD	High
			Host rock temperature (Issue 1.10)	TBD	High
		Prevent adverse degradation of packing structural properties due to preclosure temperatures	Adverse alteration of packing material physical properties due to high temperature (Issue 2.6)	<1% change	High
		Prevent adverse degradation of swelling properties due to preclosure temperatures	Irreversible dehydration temperature (Issue 2.6)	<370 °C	High
		Packing material will maintain mechanical integrity during handling operations	Handling induced strain (Issue 2.6)	TBD	High
		Packing will maintain dimensional clearances for container emplacement	Handling clearances (Issue 2.6)	TBD	High
		Limit packing interactions to prevent adverse chemical effects on the waste package components	TBD (Issue 2.6)	TBD	High
		Limit packing interactions to prevent adverse physical effects on the waste package components	Container strain (Issue 1.10)	<1%	High
		Limit packing interactions to prevent adverse chemical effects on the waste package components	Container strain (Issue 1.10)	<1%	High
	Shell	Protect preformed packing from damage during handling operations	Packing overstress (Issue 2.6)	TBD within allowable limits	High
			Altered packing physical characteristics (Issue 2.6)	TBD % change in void volume	High
			Packing inspection specifications (Issue 2.6)	Meet specifications	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 9 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Shell (cont.)	Facilitate waste package handling and emplacement	Repository throughput (Issue 2.6)	>8 waste packages per day	High
			Worker radiation exposure (Issue 2.6)	Less than 10 CFR 20 (NRC, 1987b) limits	High
		Limit shell interactions to prevent adverse physical effects on waste package components	Altered packing mechanical properties due to delay in groundwater saturation time (Issues 1.10, 2.6)	No significant change	High
	Waste package	Limit shell interactions to prevent adverse chemical effects on waste package components	Altered packing hydraulic conductivity due to interaction with shell corrosion products (Issues 1.10, 2.6)	<10 ⁻⁶ cm/s	High
		Maintain structural integrity of the waste package	Component over-stress (Issue 2.6)	Less than allowable limits	High
		Provide assembly and emplacement clearances to meet post closure void volume requirements	Component swelling pressure (Issue 2.6)	TBD	High
			Packing hydraulic conductivity (Issue 2.6)	10 ⁻⁶ cm/s	High
		Waste package identification will remain intelligible through the retrievability period	Legibility (Issue 2.6)	>84	High
			Identification traceability (Issue 2.6)	Waste package contents traceable to preemplacement records	High
		Waste package will not include explosive, pyrophoric, or reactive material	Performance measures established by administrative design controls (Issue 2.6)	TBD grams of explosive, pyrophoric, and reactive materials	High
		Waste packages will be free of liquids	Amount of drainable fluids from components (Issue 2.6)	TBD	High
		Prevent criticality due to handling operations	Effective multiplication coefficient, k_{eff} (Issue 2.6)	<0.95	High
		Limit radiation levels to prevent adverse effects on personnel during handling operations	Operating environment radiation levels (Issue 2.6)	<1 mrad/h in uncontrolled access areas	High
				<500 mrad/h for accident conditions	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 10 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Waste package (cont.)	Limit heat output per waste package to prevent adverse physical effects on the underground facility	Host rock temperature (Issues 1.10, 2.6)	TBD	High
			Host rock stress (Issues 1.10, 2.6)	TBD	High
		Limit waste package configuration to prevent adverse physical effects on the underground facility	Maximum size of waste package (Issue 2.6)	TBD	High
			Maximum size of shell assembly (Issue 2.6)	TBD	High
			Maximum weight of waste package (Issue 2.6)	TBD	High
		Limit radiation per waste package to prevent adverse chemical effects on the underground facility	Chemical alteration of backfill due to radiation (Issues 1.10, 2.6)	TBD	High
			Chemical alteration of seals due to radiation (Issues 1.10, 2.6)	TBD	High
		Limit heat output per waste package to prevent adverse physical effects on the geologic setting	Basalt strain due to areal thermal load (Issues 1.10, 2.6)	TBD	High
		Limit heat output per waste package to prevent adverse chemical effects on the geologic setting	Long-range alteration of groundwater composition due to excessive temperatures (Issues 1.10, 2.6)	TBD	High
		Limit materials interactions within the waste package to prevent adverse physical effects on the underground facility	Host rock strain due to additional stresses associated with reduced void volume (Issue 1.10)	TBD	High
		Limit heat output per waste package to prevent adverse chemical effects on the underground facility	Adverse alteration of local groundwater composition (Issue 1.10)	TBD	High
		Limit radiation per waste package to prevent adverse chemical effects on the underground facility	Chemical alteration of local groundwater due to radiation (Issue 1.10)	TBD	High

PST88-2014-8.3.4-1

Table 8.3.4.1-1. Performance measures and parameters addressed by the waste package program (sheet 11 of 11)

Performance measure and goal	Subsystem component	Component function	Performance parameter	Tentative goal	Needed confidence
Issues 1.10, 2.6, and 4.3 address same performance measures and goals as identified in Issues 1.4 and 1.5 (cont.)	Waste package (cont.)	Limit interactions within the waste package to prevent adverse chemical effects on the underground facility	Host rock stress from waste package component corrosion products (Issue 1.10)	TBD	High
		Limit interactions within the waste package to prevent adverse physical effects on the geologic setting	Basalt strain due to swelling pressures (Issue 1.10)	TBD	High
		Limit radiation per waste package to prevent adverse chemical effects to the geologic setting	Long-range chemical alteration of groundwater due to radiation (Issue 1.10)	TBD	High
		Limit interactions within the waste package to prevent adverse chemical effects on the geologic setting	Basalt strain due to corrosion product swelling pressures (Issue 1.10)	TBD	High

NOTE: The current strategy relies on solubility limits. Both stoichiometric dissolution and solubility limits cannot be invoked simultaneously for the same radionuclide.

To convert cm/s to in./s, multiply by 0.3937.

To convert cm to in., multiply by 0.3937.

To convert MPa√m to Ksi√in., multiply by 1.099.

To convert KPa to Ksi, multiply by 1.45×10^{-4} .

To convert MPa to Ksi, multiply by 0.145.

To convert g/cm³ to lb/ft³, multiply by 62.06.

^aAs needed.

^bContainer failure rate under unsaturated conditions applies to Issue 1.4 only.

^cAlternate strategy.

PST88-2014-8.3.4-1

Both a reference and an alternate strategy have been developed to address the performance issues having to do with "substantially complete containment" (Issue 1.4) and "gradual release" (Issue 1.5). The reference strategy for Issue 1.4 calls for the container and a combination of the container and packing to meet the first and then second and third U.S. Department of Energy (DOE) design objectives, respectively. Basalt Waste Isolation Project (BWIP) specific performance measures have been assigned to ensure that the design objectives are met. The alternate strategy for Issue 1.4 calls for a combination of container, packing, and waste form to meet the second and third DOE design objectives. The reference strategy for Issue 1.5 calls for a combination of the container and packing to meet the regulatory criteria, and the alternate strategy calls for a combination of the container, packing, and waste form to meet the criteria.

The investigation of candidate materials for the container and for the packing will become more focused and intensified as the program described in this Site Characterization Plan (SCP) progresses. An important criterion that will be used in the selection of component materials will be the relative chemical stability of each candidate material within the anticipated range of the waste package environment conditions. The goal is to use materials that are stable or as close to thermodynamic stability as practicable in the anticipated environmental range. Another important criterion will be the relative physical stability of practical combinations of emplacement configuration, waste package design, and material candidates for components to be able to meet the performance functions of the emplaced waste package. Resistance to loads imposed by the basalt, hydrostatic loads, and settlement of the loaded container in the surrounding layer of packing are examples of considerations that relate to physical stability and must be evaluated as part of component material selection. The goal will be to use the most practical combination of emplacement configuration and waste package design (including component materials) that will meet the performance goals for this consideration.

8.3.4.1.2 Approach to investigations

The approach used to implement the waste package program strategy is depicted in Figure 8.3.4.1-1. The figure provides a simplified overview of the process being used to develop a licensable, cost-effective waste package design on the required schedule. This process will be followed during the advanced conceptual design phase and the license application design phase. Although a diagram of this type can do much to illustrate the program, the simplified format does not depict all of the interactions that occur in the program.

The waste package development process starts with the basalt mined geologic disposal system description, which identifies the elements of the system. The site characteristics data base documents the characteristics of the Hanford Site basalt to which the waste package subsystem must be designed. The waste forms data base defines the characteristics of the waste that must be handled by the waste package subsystem. From the foregoing, the project

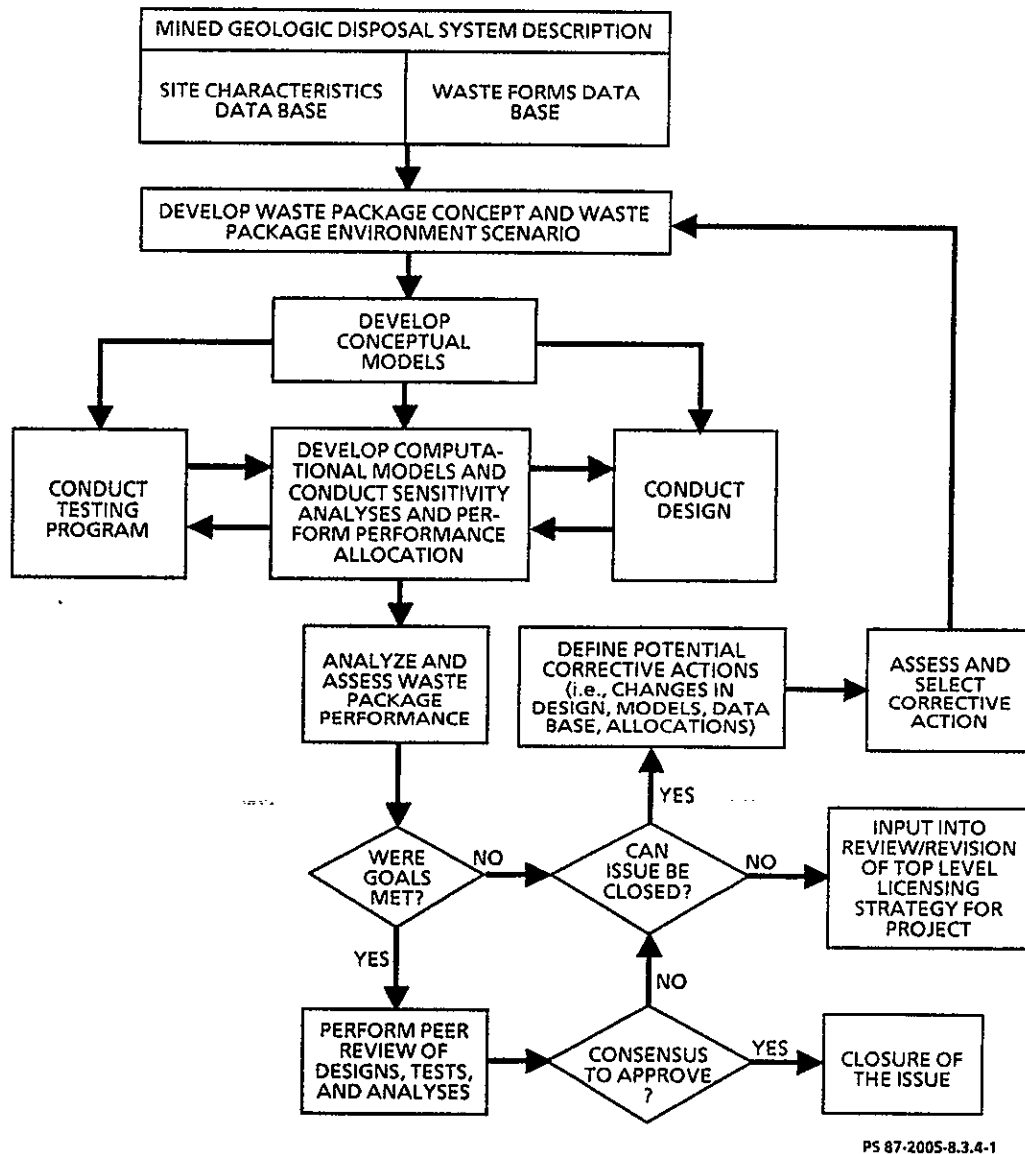


Figure 8.3.4.1-1. Waste package development process.

has developed a waste package concept and a coupled waste package environment scenario. These have been used to develop conceptual models of the processes that are expected in the postclosure period of the waste package subsystem.

During the early stages of the program, waste package computational models will be developed to describe the anticipated behavioral-related processes. These models will be used to perform sensitivity analyses and to help allocate waste package performance measure goals and needed confidence at the test and design level to guide the testing and design investigations. In the event that the testing or design goals are unattainable, the waste package models will be used to assess the effect on the related waste package performance measure goals. If needed and if possible, the waste package performance measure goals can be reallocated to assign new test and design goals. The implementation of this iterative process is important to the effective development of a waste package that will meet the applicable regulatory requirements.

The Conduct Testing Program block in Figure 8.3.4.1-1 includes specific programs for both waste package environment (Section 8.3.4.2) and waste package components and interaction testing (Section 8.3.4.3). The work in this block involves the acquisition of suitable test data to support waste package modeling and design development programs. An important aspect of this work is testing and analyses to define the waste package environment, thereby setting ranges for environmental testing variables. Also critical is the definition of relevant waste form characteristics and their influence on the environment. The waste package materials testing initially focuses on systematic, site-specific laboratory testing of candidate component materials. Assemblages of representative waste package materials will be tested to assess possible synergistic effects in waste/barrier/rock interaction tests. The solubility, speciation, and sorption behavior of radionuclides will be investigated. Testing will be conducted as a function of expected changes in the waste package environment with time (e.g., temperature and groundwater chemistry). Test data will permit the selection and verification of reference materials and development of design requirements for waste package design development. The data and mechanistic information will be incorporated into predictive models for use in performance, reliability, and safety analyses.

The Develop Computational Models and Conduct Sensitivity Analyses and Perform Performance Allocation block and the Analyze and Assess Waste Package Performance block in Figure 8.3.4.1-1 represent waste package modeling program work (Section 8.3.4.5). Identification of potential waste package degradation modes provides important information to develop waste package models. Potential degradation modes are analyzed and computational models are developed for each significant process using test data and mechanistic information provided by the testing studies and the relevant literature. Sensitivity analyses using the computational models provide guidance to testing studies and design activities by identifying the most sensitive test variables and design parameters relative to waste package performance. The computational models are also used to allocate parameter goals and needed confidence. Effective implementation of the testing studies and design

activities are heavily dependent on this guidance. The computational models also are used in a probabilistic manner to assess the performance, reliability, and safety of waste package designs.

The Conduct Design block (see Fig. 8.3.4.1-1) corresponds to the waste package design development program (Section 8.3.4.4). This block includes engineering design activities, component development studies, and the waste package qualification testing study. The waste package design process is an iterative process. Initially, a number of different concepts were considered. Through a series of updating activities, the design choices will be made that will eventually lead to the establishment of a waste package license application design. The BWIP has designated the following phases for the design process: site characterization plan conceptual design, advanced conceptual design, and license application design. At each succeeding design phase, the waste package configuration and materials specifications will be described in greater detail.

Essential to all aspects of waste package program execution is the block identified as Perform Peer Review of Designs, Tests, and Analyses (see Fig. 8.3.4.1-1). As the waste package program progresses, external expert review of all aspects of the program will be important in establishing confidence in the detailed approach and results of the program.

As the computational predictive models become operative, the performance reliability of the waste package will be analyzed and the results will be compared with the waste package performance goals established as part of the issue resolution strategies. The question asked is, "Were goals met?" If the answer is "yes," and sufficient waste package program peer review consensus is obtained via external expert review, work will proceed toward license application, and the results will be reported in the Final Environmental Impact Statement and Site Recommendation Report. If the answer is "no," the causes for failure to meet the performance goals will be analyzed. The results might indicate that (1) more test data are needed, (2) the computational models need refinement, (3) the waste package design requires some refinement, or (4) the waste package performance goals need to be reallocated.

8.3.4.1.3 Organization of Section 8.3.4

The information needs that must be satisfied to resolve waste package related issues were identified in Section 7.5 and also are presented as combined sets of parameters in issue resolution tables in Section 8.2.2. The individual studies planned to address each information need, along with related design and design analysis activities, have been combined under

appropriate investigations, which in turn have been placed into one of four specific programs, as shown in Table 8.3.4.1-2. The subsection of this document for each specific program and the purpose of each are listed below:

- Waste package environment (Section 8.3.4.2)--Define the waste package geophysical and geochemical environments as a function of time in support of testing and design programs.
- Waste package materials and interaction testing (Section 8.3.4.3)--Generate waste package materials behavior and component materials interaction information in support of design and modeling programs.
- Waste package design development (Section 8.3.4.4)--Develop a waste package design by engineering activities and development studies in conjunction with the testing and modeling programs.
- Waste package modeling (Section 8.3.4.5)--Develop computational predictive models describing waste package behavior in support of testing and design programs and to assess the ability of the waste package to meet the waste package related performance goals.

Within the waste package environment program, there are two investigations:

- Postemplacement waste package environment (Section 8.3.4.2.3).
- Natural analogs and metallic artifacts (Section 8.3.4.2.4).

The waste package materials and interaction testing program includes four investigations:

- Waste forms (Section 8.3.4.3.3).
- Container materials (Section 8.3.4.3.4).
- Packing materials (Section 8.3.4.3.5).
- Waste package radionuclide behavior (Section 8.3.4.3.6).

The waste package design development program includes four investigations:

- Design activities (Section 8.3.4.4.3).
- Container development (Section 8.3.4.4.4).
- Packing development (Section 8.3.4.4.5).
- Qualification testing (Section 8.3.4.4.6).

The waste package modeling program includes four investigations:

- Performance sensitivity (Section 8.3.4.5.3).
- Performance and reliability (Section 8.3.4.5.4).
- Impact stress and fracture (Section 8.3.4.5.5).
- Model validation (Section 8.3.4.5.6).

Table 8.3.4.1-2. Summary of waste package program investigation and studies or activities (sheet 1 of 2)

Section	Specific program	Sub-section	Investigation	Study or activity
8.3.4.2	Waste package environment	8.3.4.2.3	Postemplacement waste package environment investigation	<ul style="list-style-type: none"> • Basalt/groundwater interactions study • Geochemical environment analysis study
		8.3.4.2.4	Natural analogs and metallic artifacts investigation	<ul style="list-style-type: none"> • Waste package natural analogs study • Waste package metallic artifacts study
8.3.4.3	Waste package materials and interaction testing	8.3.4.3.3	Waste forms investigation	<ul style="list-style-type: none"> • Waste form information activity • Waste form test materials study • Waste form - filler materials interactions study • Waste acceptance specifications study
		8.3.4.3.4	Container materials investigation	<ul style="list-style-type: none"> • General corrosion study • Pitting corrosion study • Environmentally assisted cracking study • Crevice corrosion study • Mechanical and physical properties study
		8.3.4.3.5	Packing materials investigation	<ul style="list-style-type: none"> • Chemical stability study • Physical properties and processes study
		8.3.4.3.6	Waste package radionuclide behavior investigation	<ul style="list-style-type: none"> • Radionuclide solubility/sorption and speciation behavior study • Waste/barrier/rock (W/B/R) interactions: spent fuel release testing study • W/B/R interactions: borosilicate glass release testing study • W/B/R interactions: other waste forms testing study
8.3.4.4	Waste package design development	8.3.4.4.3	Design activities investigation	<ul style="list-style-type: none"> • Trade and engineering studies activity • Waste package configuration design activity • Container design and construction standard development activity • Design-for-reliability activity
		8.3.4.4.4	Container development investigation	<ul style="list-style-type: none"> • Pressure vessel container development study • Monolith container development study • Container handling and safety testing study • Nonmetallic container development study
		8.3.4.4.5	Packing development investigation	<ul style="list-style-type: none"> • Packing fabrication study • Packing nondestructive examination study • Packing handling and emplacement study
		8.3.4.4.6	Qualification testing investigation	<ul style="list-style-type: none"> • Container corrosion qualification testing study • Packing saturation qualification testing study • Container settlement testing study • Waste package in situ testing study
8.3.4.5	Waste package modeling	8.3.4.5.3	Performance sensitivity investigation	<ul style="list-style-type: none"> • Thermal transport sensitivity analysis activity • Resaturation sensitivity analysis activity • Container lifetime sensitivity analysis activity • Radionuclide release and transport sensitivity analysis activity • Radiation shielding and radiolysis sensitivity analysis activity • Geochemical sensitivity analysis activity • Structural strength sensitivity analysis activity

PST87-2005-8.3.4-2

Table 8.3.4.1-2. Summary of waste package program investigation and studies or activities (sheet 2 of 2)

Section	Specific program	Sub-section	Investigation	Study or activity
	Waste package modeling (cont.)	8.3.4.5.4	Performance and reliability investigation	<ul style="list-style-type: none"> • Thermal transport analysis activity • Resaturation analysis activity • Container lifetime analysis activity • Radionuclide release and transport analysis activity • Radiation shielding and radiolysis analysis activity • Criticality analysis activity • Structural strength analysis activity • Geochemical analysis activity • System analysis activity
		8.3.4.5.5	Impact stress and fracture investigation	<ul style="list-style-type: none"> • Container fracture analysis activity
		8.3.4.5.6	Model validation investigation	<ul style="list-style-type: none"> • Model validation activity

PST87-2005-8.3.4-2

Each of the specific programs is discussed in the subsections that follow, with primary focus on the purpose, objectives, and rationale for the investigations and summary descriptions of the associated studies (testing or test analysis work) or activities (design or design analysis work). A listing of the specific programs, investigations, and accompanying studies or activities is provided in Table 8.3.4.1-2. A study plan will be written for each study. Engineering plans will be written for the activities. These plans will provide the detailed descriptions of studies and activities required to conduct the waste package program and will be refined as the waste package related parameters and information needs or the performance goals are modified.

The schedule information provided for investigations in these programs includes the sequencing, interrelationships, and relative durations of the studies in the investigation. Specific durations and start/finish dates for the studies are being developed as part of ongoing planning efforts and will be provided in the SCP at the time of issuance and revised as appropriate in subsequent semiannual progress reports.

8.3.4.2 Specific program for waste package environment

The geochemical environment of the postemplacement waste package and disturbed zone will be significantly altered from the initial in situ basalt/groundwater environment. The reasons for these differences include the following:

- Effects from mining and constructing a repository in basalt at the Hanford Site (such as dewatering the basalt followed by resaturation of the host basalt, introduction of an oxygenated atmosphere, decrease and reestablishment of fluid pressure accompanying dewatering and resaturation of the host basalt, and introduction of construction materials).
- Effects of changes in thermal conditions resulting from waste package emplacement (such as boiling in the disturbed zone and the effects of basalt alteration).
- Chemical effects on the geochemical environment from the emplacement of the waste package (such as effects of packing and container material on the waste package environment).

The ability of the waste package to perform as an engineered barrier to radionuclide release and transport is dependent in several ways on the postemplacement environment:

- Corrosion of the container exterior is dependent on the geochemical environment. The longevity of the container may depend on the confining pressure and the extent of rock movement if lithostatic pressures occur.
- Chemical stability of packing is dependent on the environment.
- Solubility and sorptive behavior of radionuclides is dependent on the geochemical environment (particularly, redox conditions, pH, temperature, and ligand concentrations in the groundwater).

Background

Experimental programs have been established by the BWIP to evaluate the environmental effects of basalt/groundwater interactions (rocking Dickson autoclave experiments) using Umtanum and Cohasset flow basalts. Limited experimental work on the effects of radiation on the environment have been conducted. Results of these experiments (lasting up to several thousand hours) have been used to evaluate the possible mechanisms controlling post-emplacement pH and redox conditions and to assess the role of radiation on the environment. In addition, natural analog studies of Icelandic geothermal systems provided information on hydrothermal basalt/groundwater systems that have operated for thousands of years. Summaries of the experimental work to date are presented in Sections 7.4.1.1 and 7.4.1.3.4.

Summary of program

The specific program for waste package environment encompasses four studies:

- Basalt/groundwater interactions.
- Geochemical analysis.
- Natural analogs.
- Metallic artifacts.

The overall goal of this specific program is to define, in a technically correct and defensible manner, the expected environment of the waste package and the surrounding basalt for the performance lifetime of the engineered barrier system (i.e., 10,000 yr). This requires that the "bulk" environment as well as any localized environments be defined so that the performance of waste package components in the expected environments can be adequately modeled and tested. The effects of conditions during the unsaturated postclosure period, including the possibility of salinity increase with boiling and the removal of oxygen in a two-phase environment, will be evaluated analytically (Section 8.3.4.5.2).

The definition of the environment will be accomplished by conducting laboratory-scale basalt/water/waste package components interaction experiments to provide information on the evolution of these systems with time. In addition, natural analogs to the repository system and artifacts of potential container materials will be examined to determine the effects of long time periods on observed alteration assemblages. The stability of waste package materials and the waste package environment will also be determined. Numerical analysis of experimental and analog results using geochemical models will be conducted to attempt to define the processes controlling environmental conditions.

The results of the environment specific program will be documented in the form of the Waste Package Scenario Document (WHC, 1987) and revisions. Verification of the predicted environments will be accomplished, in part, by peer and technical review of these documents.

Organization of Section 8.3.4.2

This section is composed of the following subsections:

- 8.3.4.2.1--Purpose and objectives. This section describes the role of the environment specific program in the waste package program. This section also defines the specific objectives addressed by the investigations (see below).
- 8.3.4.2.2--Rationale. This section describes the role of the specific program in meeting regulatory requirements and the resolution of issues derived from these requirements.

- 8.3.4.2.3--Postemplacement waste package environment investigation. This section describes the testing and analysis activities planned to characterize the geochemical environment of the waste package and surrounding basalt.
- 8.3.4.2.4--Natural analogs and metallic artifacts investigation. This section describes the study of long-lived analogs of the basalt/groundwater environment and waste package components.

8.3.4.2.1 Purpose and objective

The primary purpose of the waste package environment specific program is to define the expected geochemical environment of the waste package and surrounding host rock that will evolve following the emplacement of waste packages in a geological repository in basalt. Values for variables such as temperature, pressure, initial and evolved groundwater composition, secondary mineral parageneses and redox conditions are used in performance assessment models developed to evaluate the ability of the waste package to meet regulatory requirements. In addition, the expected range of these environmental factors are used to define the conditions under which testing of waste package materials is conducted. A second purpose of this investigation is to evaluate to the extent possible the spatial and temporal variations in localized environments and how these environments differ from the bulk environment. Localized environmental effects may be very important in determining the performance of engineered materials (effects on the waste package due to transient boiling, effects on the container due to localized corrosion mechanisms, and the concentration of radionuclides via alpha radiolysis at the waste form/groundwater interface).

The objectives of the waste package environment program include the following:

- Defining bulk and localized redox conditions within the waste package.
- Determining the rate of oxygen consumption following closure of the repository.
- Defining the composition of altered groundwaters.
- Defining the stability (or longevity) of waste package materials via analog studies.

8.3.4.2.2 Rationale

The waste package is a major subsystem and plays an important role with respect to repository performance. The current waste package design consists of four subsystem elements that have particular functions in achieving assigned performance goals (waste form, filler, container, and packing). The performance of each of these subsystem elements when placed in the expected repository environment will ensure that the waste package will meet the criteria for the engineered barrier system at the waste package host rock interface as specified in 10 CFR 60.113(a)(1)(ii)(A) for substantially complete containment and 10 CFR 60.113(a)(1)(ii)(B) for gradual release (NRC, 1987a). Issues resolution strategies for Issues 1.4 (substantially complete containment) and 1.5 (gradual release) outline the DOE strategy to meet the above regulatory release criteria. Although no specific performance goals for the waste package environment have been established in the strategies for the resolution of Issues 1.4 and 1.5, the performance and functions of all subsystem elements for which goals are established depends on the waste package environment. Because of the environmental dependencies, the waste package environment must be well defined so that appropriate testing conditions can be established to evaluate the performance of waste package components. In addition, a knowledge of the potential ranges for environmental parameters is needed so that probabilistic analyses of waste package performance can be made.

Additional justification for the characterization of the postemplacement environment near the waste package stems from the need to obtain realistic source terms for evaluation of releases to the accessible environment under Issues 1.1 and 1.2 and releases to special sources of groundwater under Issue 1.3. The performance of the site to retard radionuclide release is a function of (in addition to groundwater travel time) the solubility of radionuclide bearing phases and the sorptive characteristics of basalt and basalt alteration products in the disturbed zone, both of which are highly dependent on environmental conditions. Furthermore, the types and abundances of the alteration minerals in the disturbed zone are a function of the postemplacement hydrothermal history of the basalt.

8.3.4.2.3 Postemplacement waste package environment investigation

The postemplacement waste package environment investigation includes both the development of numerical geochemical models of the waste package environment and the hydrothermal testing done in support of waste package environment characterization.

8.3.4.2.3.1 Purpose and objectives

The purpose of the postemplacement waste package environment investigation is to define the ranges of geochemical parameters that are expected during the repository performance lifetime with special emphasis placed on defining those parameters that are critical to waste isolation.

A single information need (postemplacement geochemical environment) supported by this investigation is identified in Issues 1.4 and 1.5.

The information collected will be used to establish the range of test conditions for waste form, container, and packing materials testing. In addition, the information will provide specific parameters, or "response surfaces" in performance assessment, to evaluate waste package performance in an evolving geochemical environment.

The objectives of the postemplacement waste package environment investigation include the following:

- The development of a numerical geochemical model of the postclosure waste package environment. The resaturation of the repository is modeled analytically as described in Section 8.3.4.5.2.
- Experimental determination of the expected redox conditions and oxygen reduction rates for the basalt/groundwater system.
- Definition of localized environments resulting from phenomena such as boiling and radiolysis.
- Definition of the conditions under which waste package components will be tested.

8.3.4.2.3.2 Rationale

Postemplacement environmental information is needed because the performance of the major waste package system elements is dependent on the environment as described below:

- Both the maximum concentration of radionuclides in groundwater and the dissolution rates of waste forms are strongly dependent on environmental parameters such as redox conditions, groundwater composition, and pH.
- The chemical stability and corrosion rate of the container are functions of the geochemical environment.
- The chemical stability of packing is influenced by groundwater composition and pH. Furthermore, the sorptive function of packing is sensitive to redox conditions.

Technical concerns have been identified (7.5.1) that must be resolved to demonstrate that waste package performance goals will be met. Several of these technical concerns require information on the waste package environment or on the waste package performance in the expected environment and must be considered in resolving Issues 1.4 and 1.5.

The summary of the current waste package data base (Section 7.5) identifies several technical concerns for which information on the expected waste package environment is needed:

- Predicting the redox evolution in the repository.
- Demonstrating that a bounding solubility value exists for a particular radionuclide that controls radionuclide release to an acceptable level.
- Predicting long-term container corrosion performance.
- Demonstrating microbial effects on corrosion.
- Predicting the effects of long-term hydrothermal alteration on packing permeability, sorption capacity, strength, and creep properties.
- Predicting the effects of repository and seals materials on waste package groundwater chemistry and waste package component properties.

The information needs required for each of the above technical concerns are met by this investigation, and a synopsis of the relevant technical strategies are presented in Table 8.3.4.2-1.

The primary constraint on the postemplacement waste package environment investigation is to predict relevant repository conditions for thousands of years based on a few years of test data. Furthermore, many of the expected environmental changes that may occur rapidly (within 10 or 20 yr) with respect to the repository timeframe are unacceptably slow for an experimental program of a 3- or 4-yr duration. In order to deal with this constraint, testing has been chosen with the goal of bracketing expected repository conditions. For example, the use of static and flowthrough experimental apparatus allows the effect of variation in flow rates and effective water/rock ratio to be evaluated. Careful comparison of short-term test results with active geothermal system and mines will be useful in establishing the time dependency of experimentally observed environmental parameters.

Mass transfer analyses of testing and natural analog results will be used to extrapolate to repository time scales. In addition, sensitivity analyses will be conducted to determine which environmental parameters are the most important and which are most sensitive to inhomogeneity in the groundwater and basalt composition. These analyses will be used to define the experimental program with the goals of characterizing only the environmental parameters needed (and to the degree needed) to establish waste package performance.

Table 8.3.4.2-1. Information needs to be satisfied by the postemplacement waste package environment investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
<p>Postemplacement waste package geochemical environment</p> <p>(1) Basalt/groundwater interactions</p> <p>(2) Geochemical environment</p>	<p>Information is required on the geochemical environment expected for waste packages in order to define experimental conditions for assessing container corrosion, determining radionuclide steady-state concentrations, spent fuel dissolution behavior and packing stability. In addition, assessment of waste package performance using mechanistic models requires that the expected waste package geochemical environment be defined.</p>	<p>Demonstrate that waste package materials can provide a reducing environment as follows: (1) Verify that the ambient conditions at the repository site are reducing. (2) Determine the amounts of oxidants introduced into the repository. (3) Identify oxidant removal mechanisms. (4) Study analog systems to evaluate long-term behavior of relevant systems. (5) Conduct testing to determine the redox behavior and capacity of the system. (6) Conduct peer reviews to ensure that calculations, models, and conclusions drawn from testing are correct.</p> <p>Conduct flowthrough and static waste form-groundwater-waste package components experiments over the expected range of environmental parameters to establish steady-state radionuclide concentration.</p> <p>Determine the nominal and bounding environmental conditions expected in the waste package and conduct tests to obtain relevant corrosion data.</p> <p>Determine from literature survey, consultation with experts and the expected waste package environment the particular strains of organisms (if any) and the size of populations that would be expected to survive in the waste package environment.</p> <p>Conduct hydrothermal experiments using packing and other waste package materials over the expected range of environmental parameters to establish the chemical stability of packing.</p> <p>Conduct hydrothermal experiments to determine what effects repository and seals construction materials have on the waste package environment, and determine if the effects are detrimental to packing performance.</p>	<p>Predicting the redox evolution in the repository</p> <p>Demonstrating that a bounding value exists for a particular radionuclide that controls radionuclide release to an acceptable level</p> <p>Predicting long-term container corrosion performance</p> <p>Demonstrating microbial effects on corrosion</p> <p>Predicting the effects of long-term hydrothermal alteration on packing permeability, sorption capacity, strength, and creep properties</p> <p>Predicting the effects of repository and seals materials on waste package groundwater chemistry and waste package component properties</p>

PST87-2005-8.3.4-31

The approach to characterize the postemplacement waste package environment is depicted in the logic of Figure 8.3.4.2-1. The approach is based on establishing and defining waste package components functions and related performance parameter goals (see Table 8.2.2.1.4-2 and 8.2.2.1.4-3 for Issue 1.4 and Table 8.2.2.1.5-2 for Issue 1.5). These functions and performance parameter goals are used to develop a test matrix based on materials and thermal histories for the waste package. Using expert judgment, test instructions and procedures are developed to conduct the testing needed to characterize the environment. The major testing activities include defining thermodynamic and kinetic data for relevant phases, determining the environmental effects of repository construction and container materials, determining the redox capacity of packing, determining the effects of radiolysis, and evaluating the effects of basalt/groundwater interactions from static and flowthrough tests. The testing activities feed environment analyses. These analyses are evaluated based on the criteria outlined in the "evaluate results" box in Figure 8.3.4.2-1. If the criteria are satisfied, then the postemplacement waste package environment is characterized. If the criteria are not satisfied, a decision of whether additional (and/or) different) tests are needed is made. If further testing is needed, additional test instructions and procedures are developed and implemented. If no further testing is needed, the geochemical models are defined and the analyses repeated.

If the characterized environment is detrimental (e.g., too oxidizing) to the performance of a waste package component, options have been identified for the technical concerns that will mitigate the adverse environment. These options are found in Section 7.5.1.

8.3.4.2.3.3 Description of studies

The postemplacement waste package environment characterization investigation is organized into two studies. The first study is the basalt/groundwater interactions study, which includes the following activities:

- Static and flowthrough basalt + groundwater + container materials + radiation hydrothermal interaction tests.
- Redox speciation and capacity tests.

The second is the geochemical environment analysis study and includes the following activities.

- Development, validation, and documentation of a geochemical model of the postemplacement waste package environment, including an assessment of the effects of lithostatic pressure on the waste package.
- Definition and determination of the thermodynamic parameters needed for the geochemical modeling effort. This activity is primarily a literature survey with limited testing.
- Analysis of the waste package environment using the developed model.

8.3.4.2-9

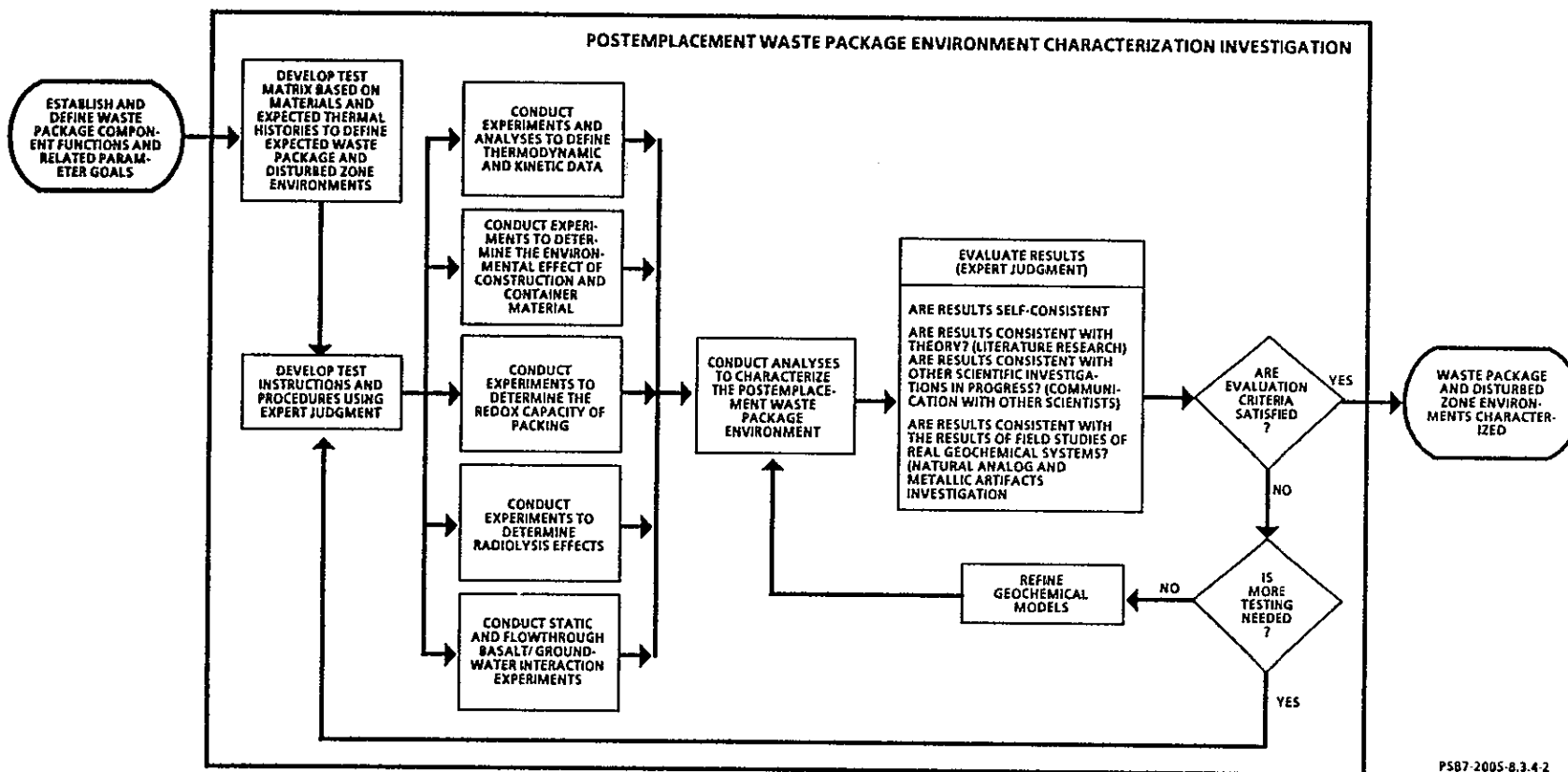


Figure 8.3.4.2-1. Logic for the waste package postemplacement environment characterization investigation.

The remainder of Section 8.3.4.2.3 is a brief description of the two studies. More detailed descriptions can be found in the Waste Package Environment: Basalt/Groundwater Interactions Study Plan (IT Corp., 1987a) and the Waste Package Environment: Geochemical Environment Analysis Study Plan (IT Corp., 1987b).

8.3.4.2.3.1 Basalt/groundwater interactions study.

The objective of the basalt/groundwater interaction study is to obtain data on the chemical evolution of basalt/groundwater hydrothermal systems. These data will include quantitative values for solution parameters (including redox state, pH, and ligand concentrations), alteration mineralogy, and reactivity of basalt over the range of temperatures expected in the post-emplacement waste package environment. The determination of redox conditions in basalt/groundwater mixtures is a major part of this study. Specifically, the capacity of basalt to impose reducing conditions on the fluid, the reversibility of redox reactions under repository relevant conditions, the redox state of the fluids (which results from reaction with the basalt), and the redox capacity of basalt are the parameters being measured. In addition, ranges for environmental parameters are being quantified through a study that compares experiments on the hydrothermal interaction of Krafla (Icelandic) basalt and groundwater with naturally occurring Icelandic basaltic geothermal fields (Section 8.3.4.2.4). The effects on the environment of container and construction materials are being evaluated. Experiments are being conducted in both closed (e.g., Dickson autoclaves) and opened (e.g., flowthrough packed columns) systems in order to bracket expected repository conditions. Testing conducted in the presence of gamma radiation fields as well as other testing in radiation fields (see Sections 8.3.4.3.4.3, 8.3.4.3.5.3, and 8.3.4.3.6.3) will allow the environmental effects of radiation to be evaluated. The goals of the basalt/groundwater study relative to the characterization of the waste package environment are the following:

- Develop conceptual geochemical models in conjunction with the geochemical environment analysis study for the mechanisms controlling solution composition observed in basalt/groundwater experiments.
- Develop conceptual geochemical models for the mechanisms involved in the hydrothermal interaction of basalt/groundwater/waste package components, and repository construction materials, which will provide a rational basis for predicting the long-term chemical evolution of the waste package environment.
- Quantify the capacity of basalt to regulate solution parameters, including pH and redox conditions, which strongly influence the mobility of radionuclides and the integrity of the engineered barriers.
- Define the environmental conditions to be used in the waste package components and interaction testing program.

A list of the planned testing, test methods, and relevant parameters determined is provided as Table 8.3.4.2-2. The testing and analyses planned for this study are described in detail in IT Corp. (1987a).

8.3.4.2.3.3.2 Geochemical environment analysis study.

The objective of the geochemical environment analysis study is to develop, verify, and validate numerical geochemical models (including data bases of appropriate thermodynamic and kinetic parameters) and conduct analyses with these models to characterize the postemplacement waste package environment. The analysis will provide the basis for predicting the thermal and spatial variations in the waste package environment. The modeling efforts are centered around equilibrium mass-action and mass-transfer codes, such as EQ3/EQ6 (Wolery, 1983) and codes used to calculate steady-state concentrations of radiolysis products in saturated and steam systems. The goals of these analyses are to quantitatively understand the following:

- The important groundwater/basalt/waste package components reactions that control the range of waste package environment parameters (groundwater composition and pH, redox conditions, and alteration mineralogy).
- The redox mechanisms and capacity for basalt-groundwater interactions.
- The concentration of radiolytic products in groundwater and the effects of these products on the waste package environment.
- The possible impact of lithostatic pressure on the waste package.
- The importance of boiling around the repository to induce chemical changes in groundwater that may affect the performance of the waste package.

In addition, geochemical analyses conducted in this study will provide a theoretical framework within which the testing described in Section 8.3.4.2.3.3.1 (basalt/groundwater interactions study) can be interpreted and further testing can be defined. If significant amounts of salt or other highly soluble minerals are expected to be concentrated at groundwater boiling fronts, the potential effects of saline groundwater on the waste package may also warrant further study. Testing in the areas of corrosion, physical, and chemical properties of packing and basalt/saline water interaction would be included in these studies.

9212550677

Table 8.3.4.2-2. Summary of tests in the basalt/groundwater interactions study (sheet 1 of 2)

Test title	Abbreviated description of test method	Data produced
Cohassett flow basalt hydrothermal reactions	Measure solution compositions, alteration mineralogy and reactivity of Cohassett flow basalt under hydrothermal, closed-system conditions (Dickson autoclave experiments)	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Extent of reaction of basalt
Packed-column hydrothermal experiments with Cohassett flow basalt	Measure solution compositions, alteration mineralogy and reactivity of Cohassett flow basalt under hydrothermal, open-system conditions (flow-through experiments)	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Extent of reaction of basalt • Effect of flow rate on alteration
Fracture-flow, hydrothermal experiments with Cohassett flow basalt	Measure solution compositions, alteration mineralogy and reactivity of Cohassett flow basalt under hydrothermal, open-system conditions (flow-through experiments)	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Extent of reaction of basalt • Effect of flow rate on alteration • Effects of hydrothermal interactions on flow
Icelandic basalt hydrothermal reactions	Measure solution composition, alteration mineralogy and reactivity of Icelandic basalt under hydrothermal conditions. Results are to be compared with identical experiments using Cohassett flow basalt and GR-4 groundwater	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Extent of reaction of basalt • Comparison of the above data with data from Cohassett flow basalt experiments
Redox capacity of Cohassett flow basalt	Determine the capacity of Cohassett flow basalt to establish and maintain reducing conditions in hydrothermal solutions by injecting oxygenated groundwater into closed-system (Dickson autoclave), steady-state experiments	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Redox capacity
Effect of copper on Cohassett flow basalt/groundwater hydrothermal systems	Determine the effect of copper and cupronickel alloys on hydrothermal systems consisting of Cohassett flow basalt and groundwater in closed systems (Dickson autoclave).	<ul style="list-style-type: none"> • Solution composition • pH at temperature • Redox conditions • Alteration mineralogy and paragenesis • Extent of reaction of basalt • Metal stability

PST87-2005-8.3.4-32

Table 8.3.4.2-2. Summary of tests in the basalt/groundwater interactions study (sheet 2 of 2)

Test title	Abbreviated description of test method	Data produced
Effects of construction materials on the waste package environment	Determine the effects of proposed construction materials on hydrothermal systems consisting of Cohasset flow basalt and groundwater	<ul style="list-style-type: none"> To be determined
Effects of gamma radiation on Cohasset flow basalt/groundwater interactions	Samples of groundwater in contact with various combinations of waste-package components are placed in a gamma radiation field	<ul style="list-style-type: none"> Radiolytic effects
Reversibility of redox reactions	Use electrochemical methods to determine the redox properties of radionuclide analogs in a basalt/groundwater system	<ul style="list-style-type: none"> Qualitative information on reversibility of redox reactions

PST87-2005-8.3.4-32

The geochemical environment analysis study comprises three separate but interrelated activities:

- Development, documentation, verification, and validation of the computer codes used.
- Compilation, validation, and documentation of the thermodynamic and kinetic data base used for the analyses.
- Waste package environment analyses using the computer codes.

The EQ3/EQ6 computer software package (Wolery, 1981) was selected for geochemical modeling. This code is maintained and supported by a group at Lawrence Livermore National Laboratory that is responsible for code development and documentation. The EQ3/EQ6 package consists of two primary codes (EQ3NR and EQ6), a thermodynamic data base, and ancillary codes for data base preprocessing.

The species distribution code, EQ3NR, calculates the speciation of a solution using a Newton-Raphson algorithm assuming homogeneous equilibrium. In addition, solution composition can be calculated from equilibrium of solution and solid phase. The mass-transfer code, EQ6, using the output of EQ3NR as a starting point calculates the stepwise results of irreversible water/rock interactions using a Newton-Raphson algorithm. This code, using the assumption of partial equilibrium, allows the calculation of complex mass transfer reactions using relatively simple algorithms.

Fundamental limitations of the current version of EQ3/EQ6 (Wolery, 1981) include:

- The lack of a complete and accurate thermodynamic and kinetic data base.
- The inability of the code to account for adsorption behavior.
- The inability of the code to deal with boiling.

Planned activities described in IT Corp. (1987b) are intended to alleviate these limitations. These activities include:

- Extensive literature review to determine the thermodynamic properties of important aqueous species and solid phases. A testing program will be initiated to collect thermodynamic data, if otherwise unavailable, for those phases that are critical to models of the waste package environment.
- Evaluation of the results of basalt/groundwater interaction experiments (see Section 8.3.4.2.3.3.1) to define apparent dissolution rates and provide kinetic data for use in environmental analysis.
- Modification of EQ3/EQ6 (Wolery, 1981) to include provisions for adsorption behavior of ions (K_d , Freundlich isotherms, ion exchange and double and triple layer models).
- Modification of EQ6 to include provisions for formation of and mass transfer to a vapor phase (i.e., boiling).

The Waste Package Environment: Geochemical Environment Analysis Study Plan (IT Corp., 1987b) is subject to several constraints. One important experimental constraint is the time required to provide applicable thermochemical data for all repository-relevant species and phases. Calorimetric studies must be limited to those phases that are critical to repository modeling for which no data currently exist. In the case of some clay and zeolite minerals, difficulty in experimental synthesis or chemical analysis of natural samples will lead to the use of estimated parameters that may be less accurate than measured parameters. Theoretical models for solid solutions in clays and zeolites are poorly developed and the development of empirical relationships based on experimental or natural solid solutions may be necessary.

Another constraint is the limitation in employing equilibrium-based geochemical models to describe the evolution of an open system. Equilibrium among many aqueous phases occurs rapidly, but some redox couples are prone to disequilibrium at low temperatures. Eh values or oxygen fugacities calculated by equilibrium models may not reflect actual conditions. Often nucleation barriers to growth of secondary phases or other kinetic constraints can result in a disparity between modeled assemblages and observed assemblages.

The computer code RADIOL (Simonson, 1983) is being considered for radiolysis analyses. The code computes the kinetics of simultaneous chemical reaction by numerical integration of the appropriate differential rate equations. The code will be modified as needed and used to calculate the concentrations of radiolytic products as a function of time and location in order to determine the effects of radiolysis on the postemplacement waste package environment.

A summary of the analyses and tests planned for the geochemical environment analysis study are presented in Table 8.3.4.2-3. The activities are described in greater detail in IT Corp. (1987b).

8.3.4.2.3.4 Application of results

The results of the postemplacement waste package environment investigation will be used to establish test condition for several of the waste package materials and interaction testing investigations (Section 8.3.4.3). Specifically, these include the following investigations:

- Container materials (Section 8.3.4.3.4).
- Packing materials (Section 8.3.4.3.5).
- Waste package radionuclide behavior (Section 8.3.4.3.6).

Waste package environment results determined in the postclosure waste package environment investigation will also be used in waste package performance assessment analyses (Section 8.3.4.5). The performance assessment model being developed will use environment input to calculate waste package performance under repository relevant conditions. The specific activities of the performance and sensitivity investigation (Section 8.3.4.5.3) include the following:

- Container lifetime analysis activity (Section 8.3.4.5.3.3.3).
- Radionuclide release and transport analysis activity (Section 8.3.4.5.3.3.4).

8.3.4.2.3.5 Schedule and milestones

The schedule and study interrelationships for the postemplacement waste package environment are presented in Figure 8.3.4.2-2. Major milestones for the investigation include the completion of the basalt/groundwater interactions study and the geochemical analyses associated with license application design and the final revision of the waste package scenario document. Other milestones are the completion of verification testing and the completion of the supporting geochemical analysis study. In addition, specific study level schedules are given in the study plans.

Table 8.3.4.2-3. Summary of tests and analyses in the geochemical environment analysis study

Test title	Abbreviated description of test method	Data produced
Determine thermodynamic parameters	Measure, estimate, and obtain from the literature thermodynamic properties of minerals and aqueous species, and incorporate the data into geochemical codes	<ul style="list-style-type: none"> • Heat capacities • Enthalpies • Entropies • Gibbs free energies • Equilibrium constants
Determine kinetic parameters	Measure rates of dissolution of reactive phases of basalt under hydrothermal conditions and determine mechanisms. Measure or estimate rates of precipitation of selected alteration phases	<ul style="list-style-type: none"> • Solution composition • Reaction rates • Reaction mechanisms
Geochemical analysis using EQ3/EQ6	Conduct speciation and reaction-path analysis of basalt/groundwater interactions, hydrothermal interactions of engineered barriers materials and groundwater, and natural analogs	<ul style="list-style-type: none"> • Speciation of hydrothermal solutions • Predicted reaction path in hydrothermal system
Radiolysis analysis	Conduct analyses using expected radiation fluxes and environmental condition to determine radiolysis effects	<ul style="list-style-type: none"> • Concentration of radiolysis product

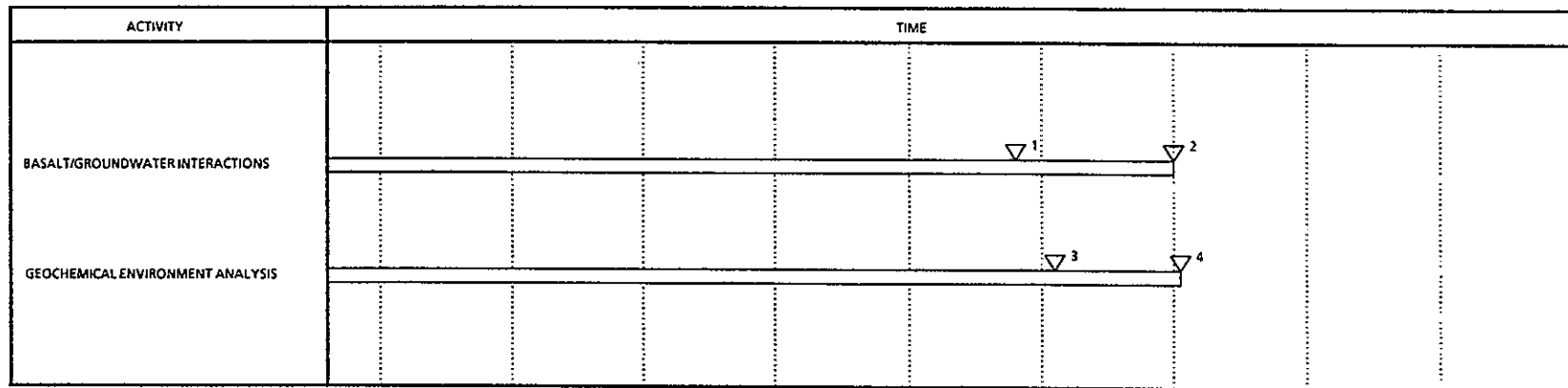
PST87-2005-8.3.4-33

8.3.4.2.4 Natural analogs and metallic artifacts investigation

The natural analogs and metallic artifacts investigation is designed to acquire data that support the experimental and conceptual models of the waste package environment, as well as data that confirm the long-term persistence of corrosion products or secondary mineral assemblages in that environment. Natural analogs to geochemical processes within the waste package environment or natural analogs to waste package materials are the subject of the studies within the investigation. Data from the studies will be compared to results of experiments or modeling to evaluate whether long-term environment behavior or material performance may be extrapolated from test data generated by experiments of limited durations.

8.3.4.2.4.1 Purpose and objectives

Two major purposes are identified for the natural analogs and metallic artifacts investigation. As part of the waste package environment specific program (Section 8.3.4.2), the first purpose of the waste package natural analogs and metallic artifacts investigation is to provide mineralogical and geochemical data to confirm the conceptual models and the experimental characterization of the waste package environment that are developed through the postemplacement waste package environment characterization investigation



PSM 2014 03 4 2

- ▽ 1 COMPLETE EXPERIMENTAL PROGRAM THAT SUPPORTS LAD GEOCHEMICAL ENVIRONMENT ANALYSIS
- ▽ 2 COMPLETE ANY REQUIRED VERIFICATION TESTING.
- ▽ 3 COMPLETE FINAL ENVIRONMENTAL ANALYSES TO SUPPORT LAD AND THE WASTE PACKAGE SCENARIO DOCUMENT
- ▽ 4 COMPLETE ANALYSES IN SUPPORT OF VERIFICATION TESTING.

LAD = LICENSE APPLICATION DESIGN

Figure 8.3.4.2-2. Postemplacement waste package environment investigation.

(Section 8.3.4.2.3). Because the rates are slow, geological processes similar to those expected to develop in the waste package environment are difficult to duplicate in controlled laboratory test because of time limitations. Natural examples of the same processes are more likely than experiments to achieve true equilibrium or some metastable steady state that would persist for repository-relevant periods of time. Information from the natural analogs and metallic artifacts investigation is used to establish a close correspondence between natural geological processes and the experimental and theoretical models of the waste package environment.

The second purpose of the natural analogs and metallic artifacts investigation is to provide data to confirm the long-term persistence of corrosion products or secondary mineral assemblages that may form during alteration of the waste package components in the repository environment. When the range of appropriate environmental parameters is determined through the waste package environment specific program, the effects of those parameters on waste package components can be tested in the waste package components and interaction testing specific program (Section 8.3.4.3). Mineralogical and geochemical data from natural analogs and metallic artifacts will be used to evaluate extrapolation of results from laboratory testing of container materials (Section 8.3.4.3.4), packing materials (Section 8.3.4.3.5), and waste package radionuclide behavior (Section 8.3.4.3.6) to repository-relevant time scales.

The performance of the major waste package system elements depends on the waste package environment (as described in Section 8.3.4.2.3.1). The primary objective of the natural analogs and metallic artifacts investigation is to establish similarities between experiments and natural occurrences that will validate the use of experimentally determined parameters in probabilistic analyses of waste package performance.

Several performance parameter goals have been set in Issue 1.4 (substantially complete containment) and in Issue 1.5 (gradual release) for the waste form and its engineered barrier components that function to limit radionuclide release. The goal pertinent to this investigation is that the maximum aqueous concentrations of specific radionuclides will be less than the goal concentration values set in Tables 8.2.2.1.4-2 and 8.2.2.1.4-3. Knowledge of physicochemical parameters of the waste package environment is required to characterize the appropriate solubility limits. The parameters are obtained from the waste package environment specific program. Confirmatory data from the natural analogs and metallic artifacts investigation support determination of the performance parameter values.

The container material, the container filler material, the packing, and the backfill (Issue 1.5 only) also function to limit radionuclide release by providing the reducing capacity needed to minimize corrosion (Issues 1.4 and 1.5) and to maintain limited radionuclide release over 10,000 yr (Issue 1.5). The performance parameter goal remains the same (i.e., to maintain maximum aqueous concentrations of specific radionuclides below the goal concentrations). The second purpose of the natural analogs and metallic artifacts investigation will provide the information on the corrosion products

or the alteration products of packing and (or) backfill needed to demonstrate that such alteration products are stable for repository-relevant lengths of time and contribute to maintaining the required reducing environment.

8.3.4.2.4.2 Rationale

The natural analogs and metallic artifacts investigation will provide information to address several technical concerns identified in a summary of the waste package data base provided in Section 7.5.1 that must be closed before the issues can be resolved. Data from the investigation will address parts of the following technical concerns:

- Predicting the redox evolution in the repository.
- Demonstrating that a bounding solubility value exists for a particular radionuclide that controls radionuclide release to an acceptable level.
- Predicting long-term container corrosion performance.
- Demonstrating microbial effects on corrosion.
- Predicting the effects of long-term hydrothermal alteration on packing permeability, sorption capacity, strength, and creep properties.
- Predicting the effects of repository and seals materials on waste package groundwater chemistry and waste package component properties.

The information needs of Issues 1.4 and 1.5 that are satisfied by data collected from the natural analogs and metallic artifacts investigation are listed in Table 8.3.4.2-4. The relationship between the technical concerns and the information needs is established in the table, and a brief synopsis of the relevant strategy for closing the technical concern is listed. The technical concerns mentioned above require synthesis of data from both the natural analogs and metallic artifacts investigation and other investigations as mentioned in Section 8.3.4.2.4.1. Both the performance parameters and the information needs supported by data from the natural analogs and metallic artifacts investigation must be addressed at the specific program level.

Several constraints dictate the formulation of studies within the natural analogs and metallic artifacts investigation. The constraints can be divided into those that are related to (1) the applicability of natural analogs and metallic artifacts studies, (2) the selection of such studies once the need for them is established, and (3) constraints that arise from schedule concerns. The details of the constraints are described below.

1. Applicability of natural analog and metallic artifacts studies-- Natural analog and metallic artifacts studies are aimed at providing confirmatory data on either the evolution of the repository environment or the persistence of materials (secondary minerals or corrosion products) in that environment. The studies are applicable

Table 8.3.4.2-4. Information needs to be satisfied by the natural analogs and metallic artifacts investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
Waste package natural analogs Waste package metallic artifacts	Saturated postclosure environment: describe saturated postclosure environment in terms of intensive parameters: temperature, pressure, fluid composition, Eh, pH.	Use natural analogs or metallic artifacts to corroborate mineralogical controls on the ambient reducing environment. Evaluate long-term behavior of repository through studies of analog systems.	Predicting the redox evolution in the repository
Waste package natural analogs Waste package metallic artifacts	Radionuclide solubility behavior: evaluate the effects of various waste package components on the solubility and sorption behavior of key radionuclides.	Use metallic artifacts studies to indicate expected long-term corrosion products. Use natural analog studies in conjunction with experimental waste/barrier/rock interactions testing to establish secondary minerals that may set upper limit on concentration of radionuclides in corrosion products at container/packing interface and within the packing and/or backfill.	Demonstrating that a bounding solubility value exists for a particular radionuclide that controls radionuclide release to an acceptable level
Waste package natural analogs Waste package metallic artifacts	Container material corrosion behavior: determine the mechanisms and products of container corrosion.	Use natural analog studies and metallic artifacts studies to confirm empirical and mechanistic models of uniform corrosion, based on test results obtained from short-term tests under bounding conditions and long-term tests under bounding and nominal conditions.	Predicting long-term container corrosion performance
Waste package natural analogs	Transport properties of packing: evaluate the effects of varying proportions and mineralogy of packing components on the physical properties of packing material.	Use natural analog studies of geothermal systems in basalt and possibly in bentonite to provide some estimate of the long-term chemical buffering capacity of the packing material, through identification of the relevant mineral assemblages.	Predicting the effects of long-term hydrothermal alteration on packing permeability, sorption capacity, strength, and creep properties Predicting the effects of repository and seals materials on waste package groundwater chemistry and waste package component properties

PST87-2005-8.3.4-35

as long as the selected analog can be characterized with enough certainty to allow further comparison to the experimental and conceptual models of the waste package environment or of material stability. Constraints are related to how well the geological or geochemical history of a natural analog or a metallic artifact can be characterized. Constraints associated with determining the geochemical evolution of a natural analog include the uncertainties associated with establishing paragenetic sequences of secondary minerals. Those uncertainties include the precision and accuracy of geothermometric or geobarometric techniques, fluid inclusion determinations, and isotopic measurements.

In order to determine a sequence of events in a natural analog, a relative time scale must be established. Some analytical methods available to establish the absolute ages of geologic settings or mineral assemblages have associated errors with magnitudes that make it difficult to quantify temporal dependency. Natural analog and metallic artifact studies can be used to define time dependency qualitatively (for example, studies by England and Thompson, 1984; Thompson and England, 1984; Staudigel et al., 1986; Chamberlain and Karabinos, 1987). Geologic relationships based on the principles of original horizontality, superposition, original continuity, and cross-cutting relationships will provide a relative time scale for natural processes, but can only confirm, rather than define, the rate expressions that can be produced experimentally. Natural analog and metallic artifacts studies are still extremely useful to establishing what assemblages are stable or persist over a geological time scale, despite constraints associated with determination of absolute ages of natural assemblages.

2. Selection of appropriate natural analog and metallic artifact studies--The following two constraints must be considered when the selection of appropriate natural analogs is being made:
 - Selection of physical and chemical conditions being studied--The compositions of the solid materials, the inferred composition of the aqueous phase, the age and duration of the events of interest, and the peak thermal and pressure loads should be similar to those that are expected to develop in the environment around the waste package. This is the only way in which a time dependency can be extracted and a good estimation of the mineral assemblages expected to persist with time can be derived from the analog situations. Where there is expected to be a range of values for an important parameter (i.e., temperature in the waste package environment), more than one geologic area may be chosen for study in order to characterize more thoroughly the effect of varying parameters.
 - Selection of materials for study--Both the waste package natural analogs study and the waste package metallic artifacts study will focus on materials that are closely similar in both chemical and physical properties to the expected waste package components.

3. Scheduling constraints--In order to conduct natural analog studies, it is necessary to have the information required to guide selection of appropriate analogs for physicochemical parameters and materials to be studied. Those data come from other investigations in the waste package program. Natural analog and metallic artifacts studies can only start after input about the expected geochemical nature of the waste package environment and the types of container and packing materials is received. Data from natural analog and metallic artifacts studies will be used to assist in the waste package material recommendations until the start of the license application design phase. Only confirmatory studies will be conducted after that time.

Tests conducted within studies that are part of the natural analogs and metallic artifacts investigation have been planned according to the constraints listed above. In the waste package natural analogs study, basalts from Icelandic geothermal fields are being evaluated as an analog to the waste package environment through comparison with basalt/groundwater experimental work. The fluid chemistry of evolving geothermal systems can be compared to the evolution of experimentally produced solutions over time. In the case of packing materials, where it is difficult to find a natural occurrence of intimately mixed basalt and bentonite, a literature study will identify a basalt-bentonite occurrence or a study of just the bentonite component of the proposed packing material will be performed.

Scheduling constraints require that preliminary environmental characterization data be available before natural analogs and metallic artifacts studies are undertaken. Knowledge of the types of container materials and the packing material is required from the applicable investigations prior to the start of natural analogs or metallic artifacts studies.

The strategy for conducting the natural analogs and metallic artifacts investigation is outlined in the logic diagram shown in Figure 8.3.4.2-3. The issue resolution strategies (Section 8.2.2) identify the function of the subsystem elements of the waste package and indicate the performance measures, parameters, and respective goals for those parameters. The data gathered in the investigations will also be used to address the related technical concerns and to establish whether closure of the technical concerns is achieved. Expert judgment will be used to produce test plans and procedures for collection of data. The major test activities will include a natural analog study of Icelandic geothermal fields, an altered bentonite deposit, and other analog and artifact studies, to be determined by literature and scoping studies. The data will be analyzed, interpreted, and subjected to thorough peer review. The results of these investigations will be made available as periodic reports and will be used to confirm the results of experimentation and modeling performed in the postemplacement waste package environment characterization investigation (Section 8.3.4.2.3), and to provide data to the appropriate investigations within the waste package components and interaction testing specific program (Section 8.3.4.3). Syntheses of data from several investigations will be used to update the appropriate design data and waste package scenario documents periodically.

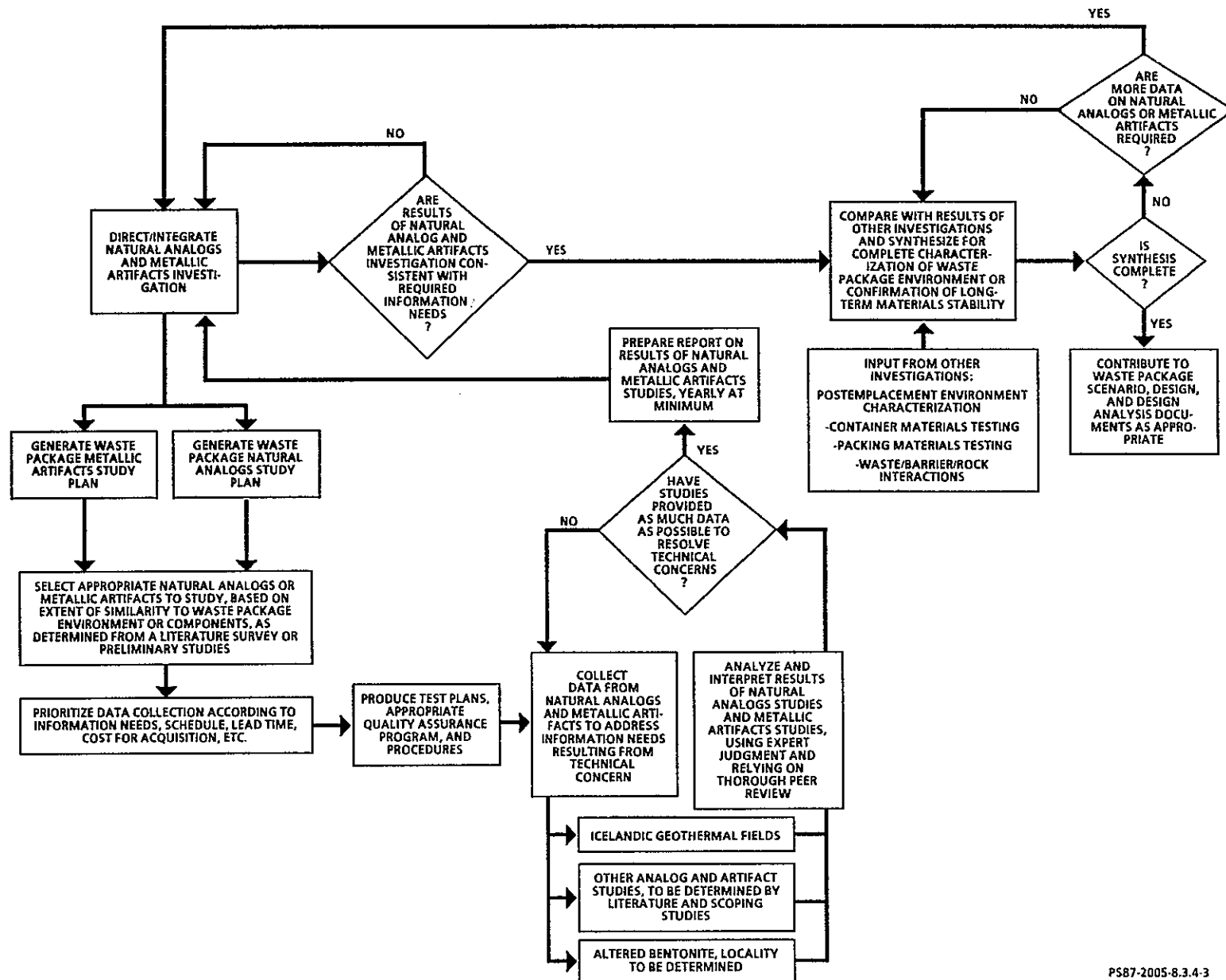


Figure 8.3.4.2-3. Strategy for the natural analogs and metallic artifacts investigation.

8.3.4.2.4.3 Description of studies

An overview of the studies comprising the natural analogs and metallic artifacts investigation is presented below. The reader is referred to the following study plans for additional details:

- Waste Package Natural Analogs Study Plan (Rawson, 1987b).
- Waste Package Metallic Artifacts Study Plan (Rawson, 1987a).

8.3.4.2.4.3.1 Waste package natural analogs study.

The purpose of the waste package natural analogs study is to provide a series of tests of geologic environments that will allow confirmation of the experimental and theoretical modeling of the waste package environment and provide an estimate of the effects of time on the stability of assemblages during evolution of the waste package environment. A description of the individual tests comprising the study and the data that will be produced are contained in Table 8.3.4.2-5. Details of the tests and analyses and the justifications for areas chosen for study are contained in the current version of Rawson (1987b).

Table 8.3.4.2-5. Summary of tests in the waste package natural analogs study

Test title	Abbreviated description of test method	Relevant parameters
Icelandic geothermal systems	Examine the data base compiled for Icelandic geothermal systems to assess the extent of the analog; determine the range of chemical compositions of groundwater and altered basalt as a function of time. Collect data on the paragenetic sequences observed in core or field relationships and use the results to predict long-term stable assemblages and inferred groundwater compositions.	Redox environment Host rock bulk composition and secondary minerals formed
Altered bentonite deposit	Conduct literature search to identify natural analogs for basalt/bentonite mixes or appropriate analogs to the bentonite component in the altered packing material. Conduct field studies, collect samples, and identify stable mineral assemblages and paragenetic relationships with the analog. Analyze minerals and determine the extent of illitization of the smectite. Establish thermal history of the alteration. Constrain age of alteration.	Degree of alteration of bentonite component of the packing material
Other natural analogs studies	Conduct literature study of possible natural analogs, including basalts that contain either native copper deposits (Section 4.3.1) or that contain native iron deposits, in order to characterize the interaction of container materials with a basaltic environment. Evaluate through literature search a possible study of calcite-cemented bentonite as an analog to the effects of cementitious material. Examine possibility of studying altered Grande Ronde basalts of the Pasco Basin in a deep borehole where temperatures can reach 120 to 200 °C. Select most appropriate analogs, according to constraints listed in Section 8.3.4.2.3.2, and conduct mineralogical and geochemical characterization studies.	Long-term stability of corrosion products Redox environment Alteration assemblages

PST87-2005-8.3.4-36

Several different geologic areas will be studied as natural analogs either to the waste package environment or to the waste package components. Two of the analogs occur in flood basalts similar in composition and age to the Columbia River basalts in the Pasco Basin that are currently being considered as the repository site. The need to establish strong chemical analogs dictated the choice of flood basalts as analogs; basalts from other volcanic or tectonic provenances are not currently under study. The study of altered basalt is designed to provide data to confirm models of the waste package environment and to establish the type and paragenetic relationships of basaltic alteration assemblages. Basalts from Icelandic geothermal fields are being studied primarily to verify experimental and analytical geochemical models of the waste package environment. The study will establish if alteration assemblages in basalt from appropriate Icelandic geothermal fields are similar to those expected in the postclosure, saturated repository environment.

Because Columbia River basalts contain no metallic iron or copper phases, it is necessary to select alternate basaltic hosts as analogs to examine the interactions of container materials with basalt. A scoping study on the occurrence of metallic iron in the Disko Island basalts of the Brito-Arctic Province in Greenland, will focus on the long-term stability of analogs to selected container materials in a basaltic environment. Earlier natural analog studies (Section 4.3.1) examined the stability of copper in a basaltic environment. A hydrothermally altered bentonite deposit (e.g., Nadeau et al., 1981; Aronson and Lee, 1986) will be identified for further study. During the early phases of the waste package natural analog study, the literature will be searched to identify other potential natural analogs and a decision will be made whether to perform additional studies of altered Columbia River basalts as natural analogs.

Icelandic geothermal systems are being assessed as an analog to the expected waste package environment through a coupled experimental and field endeavor. The composition of the basalt, the range of temperatures within the fields, and the groundwater in fields of interest are similar to those determined in the experimental work involving Columbia River basalt/groundwater interactions. Some differences in secondary minerals have been observed (see Section 4.3), but careful characterization will allow the differences to be evaluated. In the coupled experimental and field study, the results from experiments involving Columbia River basalt/groundwater will be compared to results from experiments on Icelandic basalt/groundwater. If few differences in experimental results are observed, the Icelandic experimental results will be compared to results from Icelandic geothermal fields. Secondary assemblages from geothermal fields provide data on the phases that persist for repository-relevant periods of time. The aim of the coupled study is to show that enough bulk chemical and secondary mineralogical analogies exist between Columbia River basalts and Icelandic basalts that the evolved waste package environment will be similar to that developed over time in Icelandic geothermal fields. Once the analogy is well established, thorough characterization of the paragenetic relationships within an Icelandic geothermal field is planned in order to establish the sequence of secondary phases.

The scoping study of the metallic iron and iron-carbide inclusions from basalts of Disko Island, Greenland, will be primarily a metallographic study, aimed at examining the surfaces of the metallic inclusions in order to determine the type of corrosion that could occur in a basaltic environment. Supporting mineralogical characterization will establish the extent of the analogy to the expected waste package environment and proposed container materials. The results of the scoping study will be used to evaluate whether an extended study to support repository licensing is required.

The stability of the bentonite component in the packing material over time will be evaluated by conducting a study of a natural analog that is still to be determined. The preferred analog would be that of a bentonite that has experienced hydrothermal alteration in an environment similar to that currently proposed for the waste package. After a literature search to identify an appropriate analog, field and characterization studies will be conducted to address the persistence of bentonite after repository-relevant lengths of time in a hydrothermal environment. The primary aim of the study is to evaluate the degree of alteration (probably illitization) that occurs to support design of experiments on packing chemical and physical stability (Section 8.3.4.3.5) and to establish the type of alteration products that may participate in radionuclide sorption/desorption and ion exchange in the waste package. The possible need to evaluate the role of bacteria in hydrothermally altered clay materials has also been identified.

Literature studies will be used to identify other potential natural analogs. The results of an earlier, scoping study on altered Grande Ronde basalts in northeastern Oregon (Trone and Cummings, 1987) will be used in conjunction with the results of literature reviews to determine whether to perform additional studies of altered Columbia River basalts in support of licensing a repository. Possibly those studies would be performed at depths beneath the Hanford Site, where temperatures can range from 120 to 200 °C at depths up to 3,048 m (10,000 ft).

8.3.4.2.4.3.2 Waste package metallic artifacts study.

The waste package metallic artifacts study is planned primarily as a literature search to compile and document the corrosion history of artifacts with compositions analogous to those materials that are proposed as potential waste package container materials. Artifacts experience different exposure environments for varying lengths of time; the study will concentrate efforts on interpreting corrosion in an aqueous environment similar to that expected in the repository during the postclosure phase of operation. For artifacts used as container material analogs, this study will identify the type of corrosion and the corrosion products, as well as provide characterization of the corrosion environment and the duration of the exposure. The possibility exists that artifacts will be identified for acquisition and testing. A summary of the tests planned in the study is contained in Table 8.3.4.2-6; details of the study are contained in the current version of Rawson (1987a).

Table 8.3.4.2-6. Summary of tests in the waste package
metallic artifacts study

Test title	Abbreviated description of test method	Relevant parameters
Metallic artifacts study	Conduct literature study of metallic artifacts with corrosion histories similar to those expected for the container in the repository environment. Compile information from artifacts on the exposure environment, type of corrosion, corrosion products, extent of corrosion, and duration of exposure. Examine applicability toward confirming results of laboratory testing of container materials.	Long-term stability of corrosion products

PST87-2005-8.3.4-37

8.3.4.2.4.4 Application of results

The results of this investigation will be used to support several other investigations aimed at characterization of the waste package and its individual components. Data from this investigation will be incorporated in periodic updates of the waste package environment scenario document and the waste package design data document. The scenario document is primarily a characterization tool, but the design data document will be used to perform both design and performance assessment tasks.

Periodically, data collected from studies of natural analogs and metallic artifacts will be used to (1) plan further characterization, modeling, and analysis of the basalt/groundwater system (postemplacement waste package environment investigation, Section 8.3.4.2.3); (2) provide materials characterization data to the container materials investigation (Section 8.3.4.3.4); (3) provide compositional data on starting materials for tests of the chemical and physical stability of the packing material component of the waste package (packing materials investigation, Section 8.3.4.3.5); and, (4) provide baseline data for basalt/groundwater interactions that will be used to interpret experimental results studied as a part of the waste/barriers/rock interactions testing (waste package radionuclide behavior investigation, Section 8.3.4.3.6).

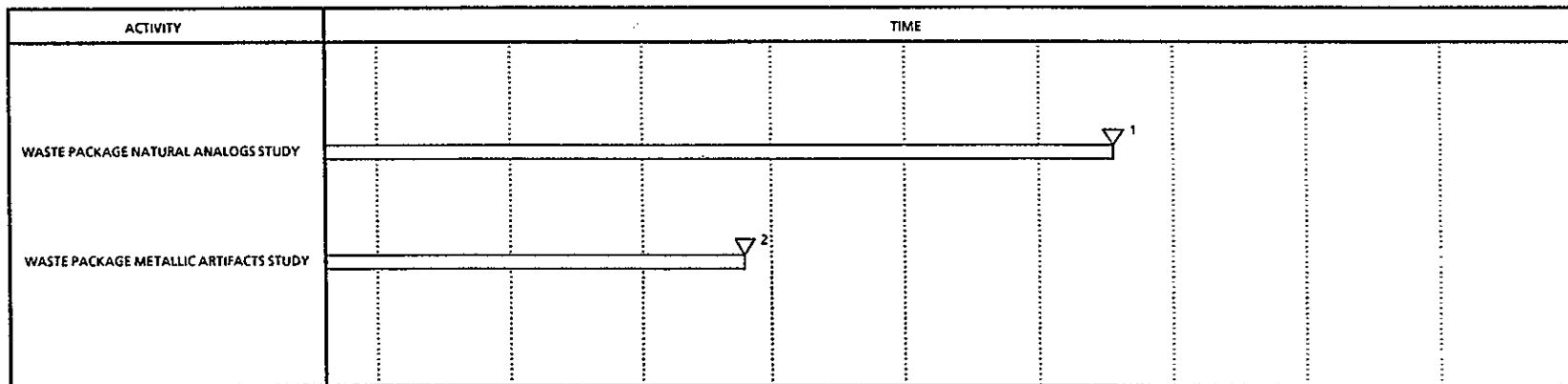
Integration of the results from this investigation with results from studies within the postemplacement waste package environment characterization investigation will occur at regular intervals. Data from natural analog studies will be used to refine the basalt/groundwater interaction testing program by providing constraints on temperature, solute concentrations, and redox conditions. Natural analog studies provide geochemical modeling studies with an indication of the secondary mineral assemblage most closely at equilibrium in the long-term waste package environment. A synthesis of the information on the waste package environment garnered from experimentation, geochemical modeling, and field studies of analogs will result from this specific program and will take the form of a conceptual model of the geochemical evolution of the waste package environment.

The waste package metallic artifacts study within this investigation provides information on the mode of corrosion and the type of corrosion products to the investigation "Container Materials," where the data will be used to refine testing and to evaluate the applicability of test data.

8.3.4.2.4.5 Schedule and milestones

The schedule and study interrelationships for the natural analogs and metallic artifacts investigation are presented in Figure 8.3.4.2-4. Major milestones for the investigation include the completion of the natural analogs study and completion of the metallic artifacts study. In addition, specific study level schedules are given in the study plans.

9 2 1 2 5 5 5 0 6 9 4



PS&B 2014-0 3.4.3

- ▽¹ COMPLETE FINAL EVALUATION OF THE PERSISTENCE OF SECONDARY MINERALS IN THE WASTE PACKAGE ENVIRONMENT, AS EVIDENCED BY NATURAL ANALOG RESULTS.
- ▽² COMPLETE FINAL EVALUATION OF THE SIGNIFICANCE OF METALLIC ARTIFACTS.

Figure 8.3.4.2-4. Natural analogs and metallic artifacts investigation.

This page intentionally left blank.

9 2 1 2 5 5 5 0 6 9 6

8.3.4.3 Specific program to test waste package materials and interaction

This section of the waste package program description provides a description of the specific program for characterizing waste package materials performance over the service life of the repository. Data generated from this program provide the materials information necessary, as defined in the issue resolution strategies for Issues 1.4, 1.5, and 1.10 in Sections 8.2.2, to design the waste package and to analyze its long-term performance.

Background

The current waste package concept is based on the present understanding of the basalt environment (Section 7.1) and limited materials performance data (Section 7.4.1 to 7.4.5). The waste package consists of the waste form (either spent fuel or canistered reprocessed waste) and a filler, sealed in a metal container that is surrounded by a packing material (crushed basalt-clay mix). A thin-walled metal shell surrounds the packing and is used as an aid for emplacing the waste package in short, horizontal boreholes.

Functions related to complying with regulatory requirements have been assigned to each component of the waste package as discussed in the issue resolution strategies presented in Section 8.2.2. The waste form is assigned the function of limiting radionuclide release during shipping, handling, and possibly during isolation. It is conservatively assumed at this time (Gilbert/Commonwealth, 1987) that the waste form, after emplacement in the repository, does not contribute to meeting long-term release performance requirements; therefore, no controlled release function is presently assigned to it. Radionuclide release is controlled by diffusion-limited mass transport of radionuclides through the packing once the packing has been resaturated. Radionuclide solubilities provide an upper bound for evaluating radionuclide release. The solubility control is provided by a stable solid phase. This is generally an alteration phase, although for some waste forms it could be the initial solid phases in the waste form itself. Should the latter be the case, then some performance functions may be assigned to the waste form in the future.

The primary function of the container is to help provide substantially complete containment of nuclear waste during repository operations and for a period of 1,000 yr after emplacement in a repository by (1) preventing water access to the waste form for a specified period of time, (2) providing structural support, and (3) providing corrosion products that can assist in limiting radionuclide release. A container filler may be used to provide additional structural support for the container, to reduce the free volume in the container, and to provide corrosion products that can assist in limiting radionuclide release.

The function of the packing is to help provide substantially complete containment and to limit radionuclide release from the waste package to levels below regulatory requirements by providing (1) a geochemically favorable environment, (2) a low-permeability medium to ensure diffusional mass

transport control of waste package releases for a period of at least 10,000 yr, and (3) support the containerized waste. Functions (1) and (2) become operable after resaturation of the packing occurs.

The shell provides for ease in handling, emplacing, and potentially retrieving the waste package.

The waste package materials and interaction testing program was established based on the waste package concept; assigned component functions; the issue resolution strategies for Issues 1.4, 1.5, and 1.10 described in Section 8.2; and current knowledge of the basalt emplacement environment. This testing program depends on the waste package environment program (Section 8.3.4.2) to identify the appropriate conditions for testing and it provides data for waste package design development (Section 8.3.4.4) and modeling (Section 8.3.4.5) programs. The design and modeling programs, in turn, provide feedback to the testing program, resulting in changes in materials or testing requirements if needed. The interactions among the four waste package programs continue until it can be shown that all waste package issues are resolved and the regulatory requirements are met. Therefore, this specific program plan will be updated as site characterization and the design effort progress.

The materials testing program consists of four investigations:

1. Waste forms (Section 8.3.4.3.3).
2. Container materials (Section 8.3.4.3.4).
3. Packing materials (Section 8.3.4.3.5).
4. Waste package radionuclide behavior (Section 8.3.4.3.6).

The waste forms investigation describes the studies necessary to characterize the various high-level waste forms proposed for disposal in a geologic repository. High-level waste forms currently under consideration by the DOE include spent nuclear fuel, reprocessed and vitrified commercial waste, reprocessed and vitrified defense waste, and limited types of commercial transuranic waste associated with spent fuel handling. Information provided by this investigation includes waste form physical and chemical characteristics, waste receipt rates and volumes, waste form acceptance requirements, and waste form-waste package materials compatibility prior to breach of the container by groundwater. The information will be used in design and design analysis to establish waste package physical dimensions, thermal loads, and handling requirements, etc. The information also will be used in testing to establish, procure, and characterize representative waste forms for use in radionuclide behavior investigations. Data also will be used to resolve technical concerns identified in Section 7.5.1.2. A more detailed summary of the waste form investigation effort is in Section 8.3.4.3.3.

The container materials investigation describes the studies necessary to provide the data base for selecting a reference material for fabricating nuclear waste containers and for predicting container materials performance under environmental conditions expected over the performance life of the repository. Information provided by this investigation includes environment-specific container materials physical and mechanical properties, environment-specific container materials corrosion behavior, and identification of corrosion modes. The information obtained will be used to select the container and shell materials, determine container thicknesses, select a preferred weld/fabrication process, determine container failure modes, and support development of container corrosion models for predicting container lifetimes. Data also will be used to resolve technical concerns identified in Section 7.5.1.2. A more detailed summary of the container materials testing investigation effort is in Section 8.3.4.3.4.

The packing materials investigation describes the studies necessary to provide the data base for selecting a reference packing material or materials for fabricating the packing component of the waste package and for predicting the packing materials performance under environmental conditions expected over the performance life of the repository. Information provided by this investigation includes environment-specific physical, chemical, and mechanical properties data; radionuclide diffusion coefficients, and packing stability/alteration data. The information obtained will be used to select a packing material or mixture of materials for fabrication, identify potential failure modes for the selected material, model mass (radionuclide) transport behavior through the packing, establish a packing fabrication process, and evaluate/model packing material stability and performance over the performance life of the repository. Data also will be used to resolve technical concerns identified in Section 7.5.1.2. A more detailed summary of the packing materials investigation is in Section 8.3.4.3.5.

The waste package radionuclide behavior investigation will provide the necessary data for evaluating the radionuclide release performance of the waste package over the performance life of the repository. Information provided by this investigation includes environment-specific waste form radionuclide release behavior (radionuclide steady-state concentrations and (or) solubilities and identification of the associated controlling solid phases), including matrix dissolution behavior, radionuclide sorption behavior in the presence of waste package materials, the effects of waste package components on radionuclide behavior, and the speciation of radionuclides in the waste package environment. This information will be used primarily to provide radionuclide source terms to the waste package release models for modeling transport of radionuclides through the packing material. The studies also provide radionuclide sorption equations for evaluating the additional radionuclide retardation potential of waste package materials and their degradation products. The data from these studies also will be used to resolve technical concerns identified in Section 7.5.1.2. A more detailed summary of the radionuclide behavior investigation is in Section 8.3.4.3.6.

8.3.4.3.1 Purpose and objectives

The objective of the waste package materials and interaction testing program is to provide the environment-specific materials performance data base required to (1) select materials, (2) design a waste package for a repository constructed in basalt, and (3) confidently predict the performance of the waste package over the repository service life. The purpose of this waste package materials and interaction testing program plan is to describe, in a summary fashion, what materials data are necessary for design and performance analysis of the waste package and how those data will be acquired and used. The data requirements for the waste package program described in this section are based on the information needs established in the issue resolution strategies for Issues 1.4, 1.5, and 1.10 (see Tables 8.2.2.1.4-2, and 8.2.2.1.4-3, 8.2.2.1.5-2, and 8.2.2.1.10-2).

8.3.4.3.2 Rationale

The scope of the waste package materials and interaction testing program is based on (1) the current design concepts (Chapter 7), (2) available analyses of waste package performance (DOE, 1986), (3) providing the information necessary to resolve the technical concerns (Section 7.5.1.2), and (4) satisfying the information needs identified in Chapter 7 and the issue resolution strategies (Section 8.2). The four investigative areas identified in the summary (Section 8.3.4.3) were based on the need to acquire materials properties and behavior data for the design of the major components of the waste package (i.e., waste form, container, and packing) and the need to evaluate waste package containment life and radionuclide release rates relative to regulatory requirements.

The testing approach adopted in the four investigations for acquiring materials data is centered on the belief that, in a repository constructed in a geologic medium, the environment will control the long-term behavior of any materials emplaced in the repository. Therefore, there is an extensive specific program to characterize the waste package environment as a function of time (Section 8.3.4.2). The range of environmental conditions defined by that program, then, provides the basis for the test methodologies developed for collecting waste package materials performance data. Thus, all materials testing for the waste package design and analysis efforts is conducted over the range of environment-specific conditions expected for a repository constructed in basalt.

To provide a measure of confidence in the materials properties and behavior data, testing also is performed under conditions considered to be outside the "norm" or over stress conditions. For example, testing at higher than expected temperatures or under more oxidizing conditions is conducted as part of evaluating many of the waste package component materials properties. Tests are also routinely replicated to provide estimates of the precision of the data and improve confidence in the data acquired.

Although every effort is made in the materials testing program to simulate expected repository conditions as closely as possible (see Section 8.3.4.2 for environment-specific program), it is not possible to simulate the long time periods over which the waste package materials must perform. The approach adopted in the materials development and testing program is fivefold:

1. Identify, to the extent possible, candidate materials for waste package engineered components (i.e., filler, container, packing, shell) that are near thermodynamic equilibrium for the long-term environmental conditions expected for the waste package. This should minimize potential degradation reactions and enhance confidence in long-term materials performance predictions.
2. Bound the possible rates and extent of identified degradation processes through mass transport and availability of reactive species evaluations and analyses.
3. Investigate and characterize natural systems and artifacts analogous to the proposed waste package component materials and expected environmental conditions. Results from these studies, when compared to laboratory results and predictive modeling results, will provide added confidence that the long-term materials performance will fall within the range of predicted values. Analog studies are generally limited to the filler, container, and packing materials.
4. Develop an understanding, to the extent practicable, of the processes and mechanisms controlling the materials properties of interest to allow predictive models to be developed and (or) used in performance modeling. Validation of these models is limited to short-term laboratory and scale-up tests and peer acceptance. The ability to confidently predict the expected environment will constrain the reliability of such materials performance.
5. Use, where feasible, relatively standard practices such as increasing temperature and increasing surface area to accelerate reactions in the laboratory testing program. Results from these types of "accelerated" tests must be interpreted with caution, however, because reaction mechanisms can change with temperature and surface area. Where accelerated test data are used to evaluate materials performance, it must be demonstrated that the reaction mechanisms have not changed as a result of the accelerated test conditions.

Therefore, using the testing approach described above and considering the technical concerns identified in Chapter 7 and the issue resolution strategies provided in Section 8.2.2, an environment-specific materials testing program was developed to provide the data necessary to design a waste package that can be demonstrated to meet long-term performance requirements with reasonable assurance. A detailed summary of the four investigations comprising this waste package materials and interaction testing specific program is provided in the following sections.

8.3.4.3.3 Waste forms investigation

The waste forms investigation comprises activities and studies that will provide the design, testing, and analysis programs with needed information on selected properties and characteristics of the reference waste forms.

8.3.4.3.3.1 Purpose and objectives

The waste forms investigation comprises the following activity and related studies:

- Waste form information activity.
 - Waste form materials study.
 - Waste form/filler materials interactions study.
 - Waste acceptance specifications study.

The waste form information activity will provide information on the characteristics, amounts, and proposed receipt schedules for the reference waste forms. Selected portions of this information will be used as input into activities such as the following:

- Waste package and repository design.
- Design analysis.
- Performance analysis.
- Establishment of test conditions simulating a given waste package environment that includes the presence of one or more of the reference waste forms.
- Establishment of compositions for simulations of high-level waste forms prepared for repository-specific hydrothermal testing.
- Development of waste acceptance specifications for reference high-level waste forms and including associated compliance tests.

The waste form materials study will provide information on the selection, preparation, and characterization (i.e., physical and chemical) of the waste form materials that will be used in designing and conducting the hydrothermal testing program of the BWIP.

The waste form/filler materials interactions study will provide information on the chemical compatibility of candidate filler materials and the spent fuel cladding materials for the applicable waste package design cases. This information on compatibility is needed to evaluate the filler candidates and to help provide the basis for selecting the reference filler material, if any, to be used in completing evaluation of the waste package design cases.

The waste acceptance specifications study will provide technical input and support to the waste acceptance process. The objective is to develop the waste acceptance specifications for the first repository. This study will include both the development of the requirements and any site-specific compliance tests that are needed to formulate these acceptance specifications. The waste acceptance specifications support the licensing program of the repository project.

8.3.4.3.3.2 Rationale

The rationale for planned activities and studies within the waste form investigation is derived from requirements to meet the system performance objectives in 40 CFR 191 (EPA, 1986) and the subsystem performance objectives in 10 CFR 60 (NRC, 1987a).

A summary of the issues, strategies, and information needs supported by the studies in this investigation is presented in Table 8.3.4.3-1.

The waste form information activity and waste form test materials study provide characterization of the source term (i.e., radionuclides) to be considered in showing compliance with the substantially complete containment and radionuclide release requirements addressed under Issues 1.4 and 1.5, respectively. Both contribute to addressing the technical concern on waste form test material representativeness (see Section 7.5.3). The waste form information activity is also a major input into the strategy for resolving the design issues (waste package engineering, Issues 2.6 and 1.10, and repository, Issue 2.4).

The primary function of the container filler material is to fill most of the residual void space present inside the container after it is loaded with the waste form. The specific study on waste form/filler materials interactions is aimed at providing assurance that the candidate filler materials will not adversely interact (chemically) with the spent fuel cladding or any exposed fuel.

The study on waste acceptance specifications provides input into the task of complying with requirements on the waste form materials per 10 CFR 60 (NRC, 1987a) and is needed to comply with the requirements of 40 CFR 191 (EPA, 1986). It will also provide input for developing acceptance specifications covering additional physical limitations (e.g., dimensions, weight, and drop test performance) resulting from the waste package and repository project design work. The waste acceptance specifications study also covers the development of site-specific testing needed to demonstrate compliance with the requirement(s) in the proposed waste acceptance specifications for each waste form.

In the waste form information activity, the primary constraint is the extent to which information is available to characterize (1) the total quantity; (2) the receipt scenario (i.e., amount of each waste type per year); (3) the physical, chemical, and radiation parameters of the waste and waste form matrix material; and (4) any canister or hardware components used for handling and shipment of the waste form material. Deficiencies in the available characterization of the reference waste forms are being addressed in this study.

Table 8.3.4.3-1. Information needs to be satisfied by the waste forms investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
Waste form information	Quantity, receipt scenario and physical, chemical thermal, and radiation characterization	Information characterizing the waste forms will be input into the performance and design issues strategies	<ul style="list-style-type: none"> • Representativeness of waste form material for testing • Issue 1.1, cumulative release • 1.4, substantially complete containment • Design issues (1.10, 1.1.1, 2.1, 2.4, 2.6, 2.7)
Waste form materials	Selection, preparation, and characterization of testing materials	Material and pretest characterization information will be provided for hydrothermal testing associated with resolving the strategies for Issues 1.4 and 1.5	<ul style="list-style-type: none"> • Technical concerns on congruent dissolution, solubility limits, waste form representativeness in Section 7.5
Waste form/filler materials interactions	Chemical compatibility of candidate container filler materials with waste form materials	Conduct predictive analysis and evaluation and confirmation testing	The technical concern is that the container filler and waste form would chemically interact and result in degrading the condition and thus performance of the waste form and (or) filler
Waste acceptance specifications	Waste acceptance requirements and associated compliance tests and procedures	Limiting requirements are identified from repository and waste package design, testing and analyses, and input into the DOE waste acceptance committee for evaluation	The technical concern is that the high level waste form being produced in a form, configuration and condition that is compatible with limits of the repository project licensing data base

PST88-2014-8.3.4-2

In the waste form materials study, the major constraints are (1) the extent of information (e.g., characteristics and fraction of total population) available from the waste form information activity on which to base the selection (e.g., spent fuel rods) or fabrication (vitrified high-level waste) of the waste form sample material and (2) the availability of the waste form material. The overall concern is to ensure that the waste form materials used in the hydrothermal test program are sufficiently representative of overall population of waste form materials proposed for disposal in the first repository. This concern about the representativeness of waste form test materials must be satisfied sufficiently to support the needs of licensing.

For the West Valley Demonstration Project commercial high-level waste and the Savannah River Plant defense high-level waste, the radionuclide-doped waste form material available for hydrothermal testing has, to date, come from laboratory-produced simulations (i.e., small-scale furnace or crucible batches). In addition, the composition of these materials has been limited to the proposed reference compositions. This is because the waste form producers are still preparing the estimated ranges of variability in the waste form composition (i.e., nonradioactive and radioactive constituents). This situation represents a current constraint regarding the technical concern for representativeness of the waste form material and the associated test data, and it is a constraint that will be addressed and dispositioned as part of the future work. As soon as estimates of the ranges in compositional variability are available, tests will be planned to obtain data that bounds the potential influence of such variability on hydrothermal test results. This will very likely involve a statistically derived testing matrix to the extent that it is practicable. The concern regarding scale (i.e., size) and representativeness of the production conditions will be addressed by using larger and more prototypical furnace facilities, as available to the respective producer programs, for fabricating representative waste form materials for testing. This effort will involve selected waste form composition cases that will provide reconfirmation-type test results. The capability exists at the Savannah River Plant to produce a large-scale prototype or sample of the proposed production material, including the use of the actual high-level waste to load the material. This will offer a material significantly closer in representing the proposed production material than the small-scale laboratory simulated versions. Such material will most likely be used as a proof test material to supplement the data base obtained using the radionuclide-doped laboratory (small-scale) simulations. Eventually, samples of actual initial production waste form material will be used to conduct some confirmation work in the repository testing programs. The aggregate uncertainty on waste form material representativeness probably will be reflected in the conclusions drawn from hydrothermal testing of these simulations.

In the case of spent fuels, the problem is one of obtaining fuel rods that are considered to be representative of the projected population of spent fuel that will be disposed of in the repository. This is further complicated by the fact that, for a significant portion of the spent fuel population proposed for disposal in the first repository, only a predicted characterization of the material is available at this time. Some of the spent fuel has not completed irradiation; much of it has not even been fabricated;

and in other cases, it has not even been designed. The approach to this constraint is to follow the literature on the demonstration testing of advanced fuel and assembly designs and to consult with the vendors and experts within the field of fuel design and performance. The DOE established a spent fuel advisory group to assist all of the repository projects in coordinating the information gathering, evaluation, and decision making needed to support the tasks of spent fuel selection, preparation, and pretest characterization. In the case of spent fuel selection, the advisory working group will continue to refine and document the selection criteria used to decide what spent fuel candidates to select for preparation and testing. Work is already underway to revise the spent fuel selection criteria, which are based on the parameters of materials characterization, including fabrication history and irradiation history, that are judged to have potentially major influences on the radionuclide release behavior from the waste form. The planned refinements in the present selection criteria will contribute to addressing the technical concern regarding representativeness of the waste form materials used in testing. Section 7.5.3.7 discusses the background of this technical concern.

Another limitation is the accuracy of values obtained for the waste form characteristics of interest. This limitation involves such things as (1) needed information that fuel vendors consider to be proprietary information, (2) the extent of past records for some parameters, (3) the capability of available analytical instrumentation to analyze the inventory, (4) the extent of secondary chemical phasing and nonuniform location of radionuclides in the waste form, and (5) the availability of validated and verified codes for predicting the radionuclide inventory. These constraints are principally being addressed by (1) obtaining a consensus of expert judgments from within the affected DOE programs as to what information is needed, (2) evaluating the relative priority of importance, (3) assessing the capability to provide the information, and (4) selecting the most practicable option to providing the information.

8.3.4.3.3.3 Description of activities and studies

The waste form investigation is currently composed of one activity and three studies. This section provides a summary description of the objectives, applications, test methods, and analyses for each activity and study.

8.3.4.3.3.3.1 Waste form information activity.

The waste form information activity will provide the BWIP programs with information needed on the waste forms to be disposed of in the repository. The information will be used to establish the input conditions for planning the design, testing, and analysis programs needed to satisfy the issue resolution strategies (see Table 8.3.4.3-1).

Site-specific testing conducted by the repository project does not have a significant role in providing this type of information (Sections 8.3.4.3.6.3.2, 8.3.4.3.6.3.3, and 8.3.4.3.6.3.4). A limited exception to this is the pretest characterization work done at the request of the repository projects on the waste form materials being prepared for hydrothermal testing. The lead

repository projects on this task have identified the types, forms, and extent of information on waste forms needed by the programs of the respective project.

The requested information is then provided by the DOE-sponsored programs specialized in the subject information and materials. For example, the prospective waste form producers will provide the information on the high-level wastes. The information on spent fuel will be provided primarily by Oak Ridge National Laboratory through the auspices of the DOE Office of Storage and Transportation Systems. The spent fuel information will be drawn from a variety of sources, such as the yearly survey of the utilities by the Energy Information Agency on spent fuel, surveys of fuel vendors, and laboratory measurements and predictive analysis work.

Analysis work associated with this particular study will be conducted by the DOE-sponsored programs specialized in the subject of the reference waste forms (e.g., Oak Ridge National Laboratory). This analysis work will focus primarily on providing the predicted values characterizing the chemical, thermal, and radiological source term relative to each reference waste form and then relating this information to the population of the given waste form (e.g., spent fuels) and the proposed receipt scenario. Codes such as ORIGEN (Croff, 1980) will be used to generate these predictive values. The Oak Ridge National Laboratory also has a program to verify and validate the ORIGEN code to support this effort.

8.3.4.3.3.2 Waste form materials study.

The waste form materials study will ensure that the following tasks are accomplished: (1) criteria to determine which waste form materials must be tested, (2) selection and acquisition or fabrication of the waste forms, (3) pretest characterization of the waste forms, and (4) preparation and supply of the waste forms materials to the testing programs of the BWIP.

The waste form materials and pretest characterization information provided by this study will be used principally in the waste/barrier/rock interactions hydrothermal testing program portion of the waste package radionuclide behavior investigation (Section 8.3.4.3.6). Some material may be used by the container materials testing investigation (Section 8.3.4.3.4).

The only testing to be done in this study will be the laboratory analysis of samples taken from the waste forms to be tested. This analysis work will contribute to the pretest characterization of these waste form materials. The primary focus of this work is characterizing the chemical inventory, phasing, and distribution within the waste form materials selected for the testing work. Several types of analytical measurement devices will be used in this work (e.g., electron microprobe, scanning electron microscopy, mass spectrometry, inductively coupled plasma spectroscopy, and x-ray diffraction). The basic pretest characterization work will be provided to all of the repository projects by the Office of Geologic Repositories via the supporting contract work of the Pacific Northwest Laboratories/Materials Characterization Center. The only pretest performed by the BWIP testing program will be, as needed, for (1) confirmation of material quality, (2) characterizing BWIP altered forms of the materials, or (3) questions raised by the hydrothermal testing results.

The only significant predictive analysis task in this study is to provide predictive values of radionuclide inventories in the waste forms. These values will be provided by or coordinated with the predictive analysis work done in the waste form information activity (see Section 8.3.4.3.3.1).

8.3.4.3.3.3 Waste form/filler materials interactions study.

There is the potential for unfavorable chemical and (or) physical interactions between the container filler material and the waste form. The consideration and evaluation of potential physical (mechanical) interactions will be addressed by the investigation on container development, which is discussed in Section 8.3.4.4. The proposed investigation on potential chemical interactions is addressed in the following discussion.

The waste form/filler materials interactions (i.e., chemical) study will provide an evaluation of the chemical compatibility between the candidate filler materials and the waste form. Filler materials are being considered for reducing void spaces within the waste form loaded container. The primary case to be considered is that for spent fuel, and especially for intact spent fuel assemblies. The primary concern in this study is the compatibility of the filler candidates and the spent fuel cladding. Although the spent fuel cladding is not being assigned a performance function as an isolation barrier, there is an interest in avoiding design and (or) component materials choices that would be predicted to significantly degrade the physical integrity of the cladding. Likewise there is the companion interest in ensuring that the filler material is not significantly degraded in its ability to fulfill the assigned performance functions. If a filler material is considered for use with any of the high-level waste forms, an evaluation may be made of the compatibility of these filler candidates and the waste form, including the canister.

The results produced by this study will be used by the waste package design and development program. The study will be restricted to the conditions corresponding to the period before breach of the waste package container. The investigation on container materials (Section 8.3.4.3.4) will address the evaluation of possible interactions between the candidate filler materials and the waste package container. The investigation on waste package radionuclide behavior (Section 8.3.4.3.6) will address the evaluation of possible interactions between the candidate filler materials and the waste form under conditions corresponding to those expected after breach of the waste package container.

This study will involve some laboratory testing of the respective candidate filler materials in combination with appropriate waste package materials. These combinations of waste package materials will be loaded into a closed test system and run under conditions simulating the range of those predicted for the reference design waste package.

The specific tests and methods of investigation to be used in this study have not been determined. The tests and methods will be determined, in part, by the selected filler material candidates. The selection of the filler materials candidates is the subject of a future engineering study task in the waste package design program.

Analysis work will be limited to data reduction and support provided to any modeling and extrapolation of the compatibility behavior determined by the study.

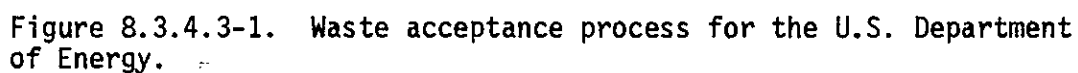
8.3.4.3.3.4 Waste acceptance specifications study.

The waste acceptance specifications study will provide input to the DOE waste acceptance process (see Fig. 8.3.4.3-1) and the tasks assigned to the DOE Waste Acceptance Committee. These efforts will result in establishing the waste acceptance specifications for each reference waste form proposed for disposal in the repository (basalt).

The waste acceptance specifications will be used by the prospective high-level waste form producers to complete the design of the waste form production process and its control. The repository project waste form producer will use the acceptance specifications to ensure that the waste form material to be shipped meets the specifications and thus the conditions of the license to operate the repository.

For each reference waste form, the final acceptance specifications will consist of a requirement and an approved method for demonstrating compliance with the requirement. For those specifications that involve meeting a requirement specific to a given repository, a repository-specific compliance method (e.g., a test) will have to be developed. As noted in Section 7.4.2.3, the specifications development work has, so far, found that only one specification needs to be site-specific with respect to the two reference high-level waste form cases (i.e., West Valley Demonstration Project and Defense Waste Processing Facility), which have been addressed, to date, by the DOE Waste Acceptance Committee. For those requirements generic to all lead repository projects, the compliance method for each specification will be selected by the DOE Waste Acceptance Committee, using input from the producers, repository projects, and supporting specialists.

For the basalt repository project, the proposed site-specific compliance test, noted above, is referred to as the BWIP-14.4 test. The objective is to obtain data from a simplified and short duration hydrothermal test that can be compared to the same type of hydrothermal testing data being derived from the more complex and longer duration testing systems that are used to establish the repository licensing data base for the given waste form case. The proposed test system uses a small-volume (e.g., less than 500 cm³ (30.5 in³)), closed, metallic vessel containing a mixture of (1) crushed and sized basalt, (2) a simulated groundwater composition specific to the basalt repository site, and (3) a sample of the given waste form in a crushed and sized condition. The waste package scenario document (WHC, 1987) and subsequent revisions will provide the information needed as to the appropriate



composition for simulating the groundwater. The test vessel system will be run for several weeks at an elevated temperature and pressure, while also being agitated to ensure mixing the constituents. Other components of the waste package system will be included in the test only if it is found that their presence is essential to achieving the objective of the test.

Test parameters, such as temperature and vessel rotation rate, will be controlled throughout the run. The test sample parameters that will be measured in the tests will be those characterizing the chemistry of the hydrothermal fluid as a function of time. Parameters such as pH, Eh, and the concentration of the respective radionuclides found in solution in the fluid will be determined. It is proposed that characterization of the solids from the tests (i.e., reaction products and condition of solids components) would only be done if results were obtained from the solution analyses that violated the final acceptance specification limits on the acceptable range of values for these data. The baseline for what is determined to be the acceptable solution chemistry (and solids results) will be established using the test data and analyses from the waste package radionuclide behavior investigation (Section 8.3.4.3.6) and the projects performance assessment analyses for radionuclide release. See Section 7.4.2.3 general remarks on the topic of this acceptance specification application by the producer and other options for demonstrating compliance.

The number of radionuclides that the test fluid will have to be analyzed for will be determined by an evaluation of results from the waste package radionuclide behavior investigation (Section 8.3.4.3.6), waste package modeling (Section 8.3.4.5), and performance analysis (Section 8.3.5.2) programs.

The data base for the BWIP-14.4 test development will be limited to that needed to develop and qualify this compliance test. This limited data base will be available for use, as appropriate, in the predictive analysis efforts that apply such solution chemistry data.

8.3.4.3.3.4 Application of results

The waste form information activity will provide various types and levels of input information and data to many of the investigations in the basalt repository project, such as (1) the waste package program (Section 8.3.4), (2) the repository program (Section 8.3.2), and (3) the performance assessment program (Section 8.3.5). Section 8.3.4.3.3.3.1 provides more details on the types of information being provided to these programs and investigations.

The waste form materials study primarily will provide material and pretest characterization information and data for the waste package radionuclide behavior investigation (Section 8.3.4.3.6). Some material may also be needed by the container materials testing investigation (Section 8.3.4.3.4).

The waste form/filler materials interactions study will provide information and data to the waste package design activities investigation (Section 8.3.4.4.3) and to waste package modeling program investigations (Section 8.3.4.5).

The waste acceptance specifications study primarily supports the licensing program of the repository system. This study is a summary-type activity for the BWIP and is basically a receiver of information rather than a provider with respect to other investigations in the BWIP. It is based on the input from major programs in the BWIP such as the repository and waste package designs, design analysis, performance assessment, licensing, and quality assurance. The other input comes from the prospective producers of the waste forms and from various Federal regulations.

In addition to providing support to other investigations, the waste form information activity directly provides major input into the performance assessment program in the BWIP. This input consists primarily of the radio-nuclide source term characterization. The waste acceptance specifications will provide some limiting parameter conditions for given waste forms.

Finally, the waste form information activity provides a major input to the design programs of the BWIP. Both the repository and the waste package design development programs are heavily dependent on such information. Chemical, physical, thermal, and radiation characterization of the waste forms, along with information on quantities, receipt schedule, etc., will be included or referenced in the design requirements documentation for the BWIP (i.e., the Site-Specific Mined Geologic Disposal System Requirements Document and the Mined Geologic Disposal System Design Requirements Document). The waste acceptance preliminary specification documents will assist in providing limiting conditions for waste form parameters that will be considered in the waste package and repository design programs.

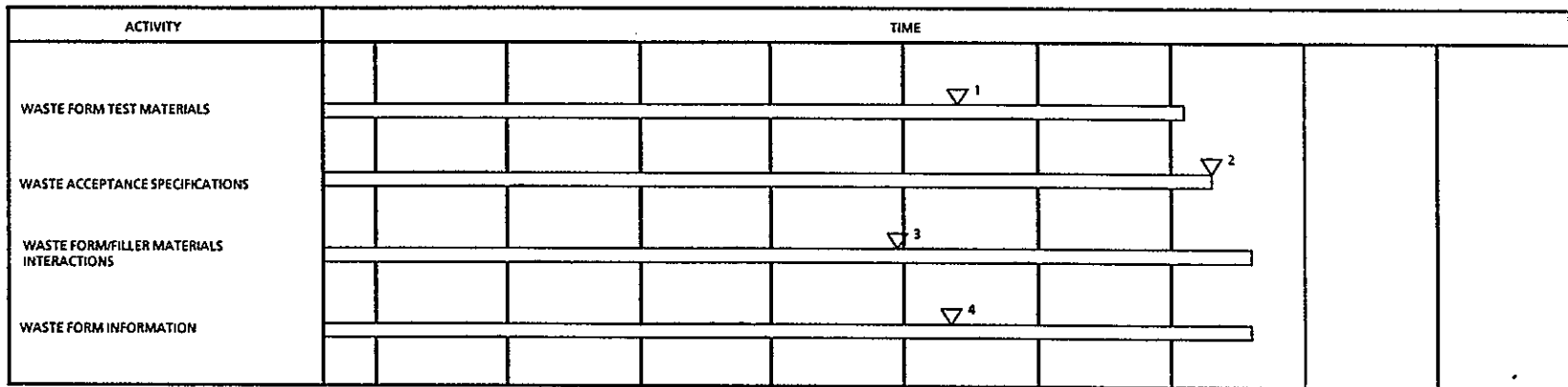
8.3.4.3.3.5 Schedule and milestones

The schedule for the waste forms investigation is provided in Figure 8.3.4.3-2. The investigation is composed of three studies and one activity. Descriptions of the major events constraining these are provided with the schedule.

8.3.4.3.4 Container materials investigation

The following sections describe the container materials investigation. This investigation has the objective of providing testing and analysis to demonstrate that the container material can meet the regulatory performance requirements. The investigation description includes four separate studies addressing the specific corrosion modes felt to be most significant and a study which will describe the mechanical and physical properties required by this investigation and others requiring container material properties.

The studies are (1) general corrosion, (2) pitting corrosion, (3) environmentally assisted cracking, (4) crevice corrosion, and (5) mechanical and physical properties. Other corrosion modes than those named are addressed under the first four study plans.



P566-2014-0.3.4-4

- ▽¹ OUTPUT TO UPDATE WASTE/BARRIER/ROCK STUDY PLANS.
- ▽² FINAL 14.4 COMPLIANCE TEST.
- ▽³ FINAL REPORT ON WASTE FORM/FILLER MATERIALS COMPATIBILITY.
- ▽⁴ BASELINE WASTE FORM DATA TO START WASTE PACKAGE LICENSE APPLICATION DESIGN.

Figure 8.3.4.3-2. Waste forms investigation.

8.3.4.3.4.1 Purpose and objectives

The information obtained from this investigation will be data from corrosion experiments, analyses of data, and predictions of corrosion behavior of candidate container materials. The data will include corrosion penetration or material degradation values and assessments of expected behavior from existing literature and theory. Recommendations will be included for ranking of container materials according to expected corrosion behavior and for selection of the final reference material during license application design. Information will be in the following forms: (1) raw data in a controlled data base; (2) physical and mechanical property data necessary to support design in a periodically updated design data document; (3) analyses of data, such as empirical corrosion correlations or degradation behavior descriptions, in a periodically updated design data document; and (4) topical reports presenting data and data evaluation. Corrosion behavior information will be used as input to the performance and reliability investigation (Section 8.3.4.5.4) to enable probabilistic estimates of container lifetime to be made. Corrosion behavior information will also be used, through the interface with the waste package modeling program, to set corrosion allowance dimensions for the container. The corrosion allowance dimensions will be determined by the waste package design development program (Section 8.3.4.4).

Corrosion behavior information is needed for satisfaction of the goals of the issue resolution strategies for Issues 1.4 and 1.5.

The container materials investigation is necessary in order to show that a sufficient fraction (greater than 0.8) of containers will not breach for 1,000 yr to meet the Issue 1.4 design objective for substantially complete containment. This will be done by providing corrosion test data and analyses and mechanical property data that support the design objective and the waste package modeling predictive codes for container lifetime. Both corrosion resistance and mechanical deformation resistance will be investigated. Additionally, the container lifetime predictive codes will allow prediction of a distribution of breaches which will show that the fractional inventory radionuclide release will be less than 10^{-5} in any year during the containment period. For Issue 1.5, the corrosion test data and analyses and mechanical property data will support the predictive code description of container breach distribution for the gradual radionuclide release period of 10,000 yr.

The significant container functions, performance parameters, and goals to meet Issues 1.4 and 1.5 objectives are in Sections 8.2.2.1.4 and 8.2.2.1.5.

8.3.4.3.4.2 Rationale

The rationale for the container materials investigation is the need to resolve Issues 1.4 and 1.5 and the following container-related technical concerns: (1) predicting long-term container performance; (2) microbial effects on corrosion, and (3) container failure rate and its effect on radionuclide release. Information obtained as a result of this investigation plan will lead to resolution of the issues and the related technical concerns. The concerns are listed in Section 7.5 with available options if the concerns cannot be satisfied.

The container materials investigation will also support the resolution of the waste form technical concern of steady-state concentration limited radionuclide release. This will be done by providing a description of the corrosion products expected from container materials degradation. Corrosion products of steel would be expected to aid significantly in establishing reducing conditions near the container, which will be beneficial from the standpoint of limiting radionuclide release. The information needs, technical concerns, and synopses of strategies for the technical concerns are given in Table 8.3.4.3-2.

A constraint for this investigation is the description of the expected waste package chemical and thermal environment, both bulk and local, which the testing and analysis program requires. A central feature of this environmental description will be an assessment of the maximum concentration of groundwater species expected as a function of time and temperature. All conclusions from the container materials investigation must be termed preliminary until this description is considered sufficiently accurate by the DOE, based on project technical judgment incorporating responses to technical review. Environmental descriptions will come from the postemplacement waste package environment investigation (Section 8.3.4.2.3), which will describe the environment of the waste package. An environmental scenario document will be used for the environmental description. Other components of the waste package subsystem and their interaction with the container must be considered, and their effects will be included in the environmental description. The description of packing material, including expected composition and impurity ranges, adjoining the container will come from the packing materials investigation (Section 8.3.4.3.5) while descriptions of filler material used within the container will come from the design activities investigation (Section 8.3.4.4.3). Description of the waste form will come from the waste forms investigation (Section 8.3.4.3.3). As these parts of the container environment are defined and reference materials are chosen, they will be included in the container materials investigation as appropriate. Reference and alternate container materials will be chosen by the waste package design development program (Section 8.3.4.4), incorporating recommendations from the container materials investigation. Reference and alternate design concepts will be chosen at the 30% advanced conceptual design point, and the final design concept will be chosen at the 30% license application design point.

A second constraint existing on this investigation is the need to categorize corrosion modes that occur in the actual repository environment, according to the DOE interpretation of anticipated processes and events as those having a probability of one chance in ten or greater of occurring during the period of concern. Anticipated corrosion modes will be accommodated in the waste package design, as required in 10 CFR 60 (NRC, 1987a), by including in the design some feature such as an added container wall thickness to accommodate corrosion and ensure the required container lifetime performance. An example of a corrosion mode that is expected to have a reasonable probability of occurrence for any of the candidate container materials is

Table 8.3.4.3-2. Information needs to be satisfied by the container materials investigation (sheet 1 of 2)

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
<ul style="list-style-type: none"> • General corrosion • Localized corrosion • Environmentally assisted cracking • Material and physical properties of container materials 	<ul style="list-style-type: none"> • Description of anticipated general corrosion container degradation and expected degradation rates • Description of anticipated pitting container degradation and expected degradation rates • Description of anticipated environmentally assisted cracking container degradation • Description of container material mechanical and physical properties for use in design and performance assessment 	<ul style="list-style-type: none"> • The anticipated credible range of environmental conditions (including local environments) will be defined and bounding conditions will be established for material degradation from environmental interaction. All corrosion modes will be assessed and those considered to be anticipated within the bounding conditions will be investigated in the testing program. If unanticipated the reasons for the choice will be documented. Short-term and extended-term tests, including accelerated tests, will be conducted to establish and confirm the bounding conditions for degradation modes; for some localized corrosion mode test conditions will be forced to yield material failure to develop a better understanding of behavior. Existing theory and data will be searched and both empirical and mechanistic-based modeling will be used to develop predictive models to the extent practicable. The models will be validated on the basis of extended-term (> 10 yr) confirmation tests. Technical peer review recommendations will be incorporated at every stage of the strategy. 	<ul style="list-style-type: none"> • Predicting long-term container performance
<ul style="list-style-type: none"> • General corrosion • Localized corrosion • Environmentally assisted cracking • Mechanical and physical properties of container materials 	<ul style="list-style-type: none"> • Description of anticipated general corrosion container degradation and expected degradation rates • Description of anticipated pitting container degradation and expected degradation rates • Description of anticipated environmentally assisted cracking container degradation • Description of container material mechanical and physical properties for use in design and performance assessment 	<ul style="list-style-type: none"> • The strategy will be initiated with a conservative description of the possible localized changes in the container environment that might occur through microbial activity. The description will come from literature studies and consultant expertise, which will be used to form an estimate of strains and population sizes of microbes, their byproducts, and effects on corrosion degradation. Testing will utilize cultures of the expected microbial types and/or their byproducts to confirm predicted effects on corrosion of container materials. Anticipated mechanisms of microbial corrosion will be factored into the predictive models for general or localized corrosion as necessary. 	<ul style="list-style-type: none"> • Microbial effects on corrosion

PST87-2005-8.3.4-18

Table 8.3.4.3-2. Information needs to be satisfied by the container materials investigation (sheet 2 of 2)

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
<ul style="list-style-type: none"> General corrosion Localized corrosion Environmentally assisted cracking Material and physical properties of container materials 	<ul style="list-style-type: none"> Description of anticipated general corrosion container degradation and expected degradation rates Description of anticipated pitting container degradation and expected degradation rates Description of anticipated environmentally assisted cracking container degradation Description of container material mechanical and physical properties for use in design and performance assessment 	<ul style="list-style-type: none"> Container failure is expected to occur by a breach or structural collapse, as a result of container wall thinning or penetration by one of several possible corrosion modes (general corrosion, pitting, etc.). Each anticipated mode will have a model with a rate equation. These will be used together to provide a container failure distribution, with Monte Carlo simulations performed on the container lifetime using appropriate distributions for the corrosion equation parameters. The failure distribution and expected releases from individual containers (obtained from the CHAINT-MC code) will be input into the REPREL code to estimate the fractional radionuclide releases from the repository. 	<ul style="list-style-type: none"> Container failure rate and its effect on radionuclide release
<ul style="list-style-type: none"> Radionuclide solubility behavior 	<ul style="list-style-type: none"> Maximum steady state concentration of specific radionuclides in the presence of groundwater and container corrosion products 	<ul style="list-style-type: none"> See SCP Section 8.3.4.3.5, Waste Package Radionuclide Behavior Investigation, for synopsis of relevant strategy. 	<ul style="list-style-type: none"> Steady-state concentration limited radionuclide release

PST87-2005-8.3.4-18

uniform corrosion. Environmentally assisted cracking of a steel container would be anticipated if the stresses were of sufficient magnitude. Thus, the design of a steel waste container must have its service stresses minimized, particularly in weldment areas, which are often trouble areas for environmentally assisted cracking in service. Pitting corrosion would be anticipated in a carbon steel container if sufficient oxygen were available during groundwater exposure; thus, a corrosion allowance could be incorporated in the design of the container wall. However, the repository groundwater is expected to become anoxic after closure (see Section 8.2.2.1.4), and analyses to date have shown no tendency for pitting in carbon steel and copper alloys in anoxic groundwater. All other corrosion modes are judged to be either unanticipated or to have insufficient information at present to determine their probability. This does not mean that those modes will be ignored in testing or analysis; the limited amount of applicable data available now and the potentially severe consequences of corrosion require a continuing investigation effort.

A position paper providing a preliminary assessment regarding anticipated container material corrosion behavior will be an early milestone for this investigation. This report will summarize existing theory and data applicable to the materials and environments of interest and discuss the implications for waste container degradation. The paper will include a preliminary assessment of the probability of occurrence of corrosion modes, as discussed previously. The position paper will be updated periodically to support the continuing waste package design efforts. The position paper will be used to support the choice of the container material for the waste package.

The schedule for site characterization presents a constraint in that it places a limit on the time available for corrosion testing and data evaluation. Test methods must be utilized that will provide necessary data in the shortest possible timeframe for the data evaluation and modeling that will be done to support the site selection decision and the license application.

The container materials investigation is not constrained by the design and construction of the Exploratory Shaft Facility. Exploratory shaft studies have potential for constraint if they indicate that the waste package environment is significantly different from that assumed in materials testing. The level of confidence in environmental data obtained from borehole testing and other means is high enough that container materials testing and analysis will proceed prior to obtaining exploratory shaft data.

Constraints exist for specimen availability. The waste package design development program will provide test specimens of prototypic container material and weldment material for corrosion testing. These must be provided far enough in advance of need dates for materials selection milestones to allow sufficient time for testing and evaluation.

Briefly, the reference strategy for Issue 1.4 is to rely on the container and packing as complementary barriers and show that together they are capable of meeting the DOE design objectives for substantially complete containment for 1,000 yr with high confidence. This strategy requires the container materials investigation to obtain data on corrosion degradation, perform empirical estimates of degradation with statistical parameters, and provide descriptions of mechanisms and processes of corrosion. The strategy requires incorporation of corrosion degradation and design parameters into a comprehensive probabilistic code. Issue 1.4 will be closed if the probabilistic code can demonstrate with high confidence container lifetimes of 1,000 yr or greater for 80% of the containers, can show that the distribution of container lifetimes will assist in controlling releases during the containment period, and can be defensible during technical peer reviews.

In summary, the reference strategy for Issue 1.5 is to rely on the container and packing as a set of complementary barriers to meet the gradual radionuclide release requirements with high confidence. The elements of the strategy from the container materials investigation standpoint are identical to those for Issue 1.4, except that the distribution of container lifetimes will be estimated for the 10,000-yr release period.

A logic diagram to describe the high-level activities in the container materials investigation is given in Figure 8.3.4.3-3. Corrosion behavior information, with supporting information from metallic artifacts (see Section 8.3.4.2.4) and long-term materials stability studies (see Section 8.3.4.3.4.3.5), will be used in the design and modeling processes to ensure that the waste package design can accommodate any expected corrosion. Peer review will be used to ensure that methods and analyses have a sufficiently broad acceptance in the technical community.

8.3.4.3.4.3 Description of studies

Descriptions of the studies within the container materials investigation are given in this section, including tables presenting the various tests and test methods to be used for each study, along with the relevant parameters to be examined by each test type.

The pertinent information need for this study is general corrosion, with a performance parameter of maximum uniform corrosion penetration in 1,000 yr. The ability to meet the parameter goal will be addressed through laboratory testing and theoretical studies leading to empirical corrosion rates and ultimately to mathematical predictive models based on mass transport/mechanistic considerations.

General corrosion is characterized by a chemical or electrochemical reaction, which proceeds fairly uniformly over the entire surface of a material exposed to a corrosive environment. One objective of the general corrosion study is to determine the rates of general corrosion of candidate container materials in both nominal and bounding condition repository

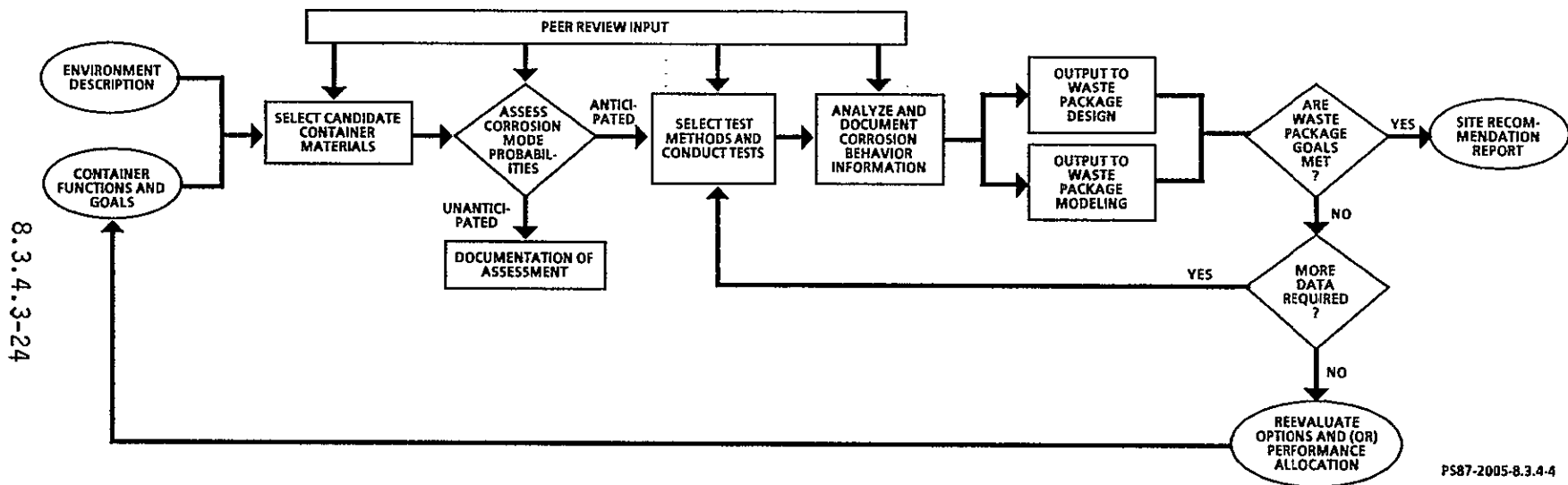


Figure 8.3.4.3-3. Container materials investigation logic diagram.

9 2 1 2 5 5 0 7 2 1

environments. These environments will be chosen from data taken from actual groundwater sampling and from analyses of expected changes in the repository environment as a function of the time, repository activities, and waste emplacement (including such aspects as galvanic corrosion and possibly effects of microbiological activity). An additional objective is formulation of a behavioral description of general corrosion, describing the underlying mechanisms and reactions. This description will be based on existing literature and theory and corrosion product analysis. This information will be used to aid in development of a mass transport based model by the waste package modeling program (Section 8.3.4.5). The model is expected to provide bounding predictions of corrosion rates for corrosion processes relevant to the waste package environment and will be used in conjunction with empirical models developed from the rate information of the general corrosion study for a complete description of corrosion processes. The study also includes analysis of general corrosion specimens for intergranular corrosion, selective leaching (in alloys), and pitting. Pitting corrosion is also the subject of a separate study (Section 8.3.4.3.4.3.2).

The primary test method is measurement of general corrosion degradation by weight loss. Specimen surface characterization by optical metallography will also be carried out to supplement weight loss measurements and to examine surfaces for other corrosion modes. Corrosion product analyses will be performed by x-ray diffraction, auger electron spectroscopy, and electron microprobe analysis. Solution product analyses will be performed to detect influences of material/environment interactions on the environment. Test variables examined will be temperature, groundwater and vapor phase composition, filler and packing material composition, container material composition, effects of fabrication and closure methods, variable surface effects (such as finish or scale effects), irradiation, and time. Table 8.3.4.3-3 summarizes the tests and parameters for the general corrosion study.

The study results will be used to construct empirical estimates of corrosion degradation rates, using regression analysis techniques of curve fitting of corrosion penetration (obtained from weight loss measurements) as a function of time for appropriate material and environment variables. The study results will serve as input to the performance assessment activity of container lifetime modeling with probabilistic does. Results will also guide container design by providing necessary information for choosing the portion of container wall thickness arising from corrosion allowances. The study will provide corrosion product definition to be used in determining the reducing nature of the groundwater environment, which is important in controlling both corrosion processes and for effects on steady-state concentrations of radionuclides. The corrosion behavior information will also be used to guide choices of reference container materials, closure methods, filler materials, and packing materials.

Table 8.3.4.3-3. Summary of tests in general corrosion study

Test title	Abbreviated description of test method	Relevant parameters
• Air/steam test	• Measure weight loss of specimens exposed to vapor environment	<ul style="list-style-type: none"> • Uniform corrosion rate • Transport properties for dissolved gases through packing and corrosion products
• Aqueous corrosion test	• Measure weight loss of specimens exposed to aqueous environment	<ul style="list-style-type: none"> • Uniform corrosion rate • Transport properties for dissolved gases through packing and corrosion products

PST87-2005-8.3.4-19

The study will be described in greater detail in the Container Materials Testing: General Corrosion Study Plan (Anantatmula, 1987).

8.3.4.3.4.3.2 Pitting Corrosion Study.

The pertinent information need for this study is localized corrosion, with a performance parameter of maximum localized corrosion penetration in 1,000 yr. The ability to meet the parameter goal will be addressed through laboratory testing and theoretical studies leading to empirical corrosion rates and ultimately to mathematical predictive models based on mass transport/mechanistic considerations.

Pitting occurs as the result of localized breakdown of a passive corrosion film followed by sustained anodic dissolution of the base metal at one or more localized sites.

The objective of the pitting corrosion study is to determine if pitting will occur in the candidate container materials in both nominal and bounding condition environments and to characterize the pitting behavior if it does occur. Any material that exhibits pitting at rates unacceptable for design under conditions relevant to the repository will be discarded. Pitting specimens will be examined for other corrosion modes such as general corrosion, selective leaching, or intergranular attack.

Pitting corrosion behavior information will be used to support analyses of pitting rates, if appropriate. Analyses may include statistical confidence limit estimation and regression curve fitting. The pitting corrosion study will provide information for development of a behavioral description for pitting corrosion, relevant to the materials and environment of interest. This description will include the most probable mechanisms and reactions responsible for anticipated and observed passive film behavior and pitting and an assessment of the persistence of the behavior over the containment period and controlled release period. It will also include estimates of rates of processes.

Pitting corrosion will also be addressed in the mechanistic corrosion model being developed within the waste package modeling program (Section 8.3.4.5). This model is based on transport limitations of available reactants and is expected to provide bounding predictions of corrosion rates for localized corrosion modes such as pitting. The pitting corrosion study will guide the waste package modeling efforts by providing degradation rate information and corrosion mechanism information for container lifetime modeling. The study will also guide design efforts in providing degradation rate information to be used in the determination of corrosion allowances. Corrosion behavior information will also guide choices of reference container materials, closure methods, and filler and packing materials.

Test methods to be used include potentiodynamic polarization curves to determine whether a passivation film can form on the container materials and, if such a film can form, electrochemical potential regions required for film breakdown where pitting could possible. Corrosion monitoring tests will ascertain the long-term stability of the actual corrosion potential of the material relative to pitting or breakdown potentials in the repository environment. Exposure of thin-walled specimens to expected groundwater-saturated packing material will result in establishing the kinetics for pitting if it were to occur in the container material (appropriateness of thin-walled specimen usage will depend on assessments of pitting probability based on polarization data). Table 8.3.4.3-4 summarizes the tests and lists the generic parameters that will be generated by this study. Solution chemistry analysis will also be performed. The parameters may not be measurable in experiments for all conditions and, thus, will only apply if measured.

Table 8.3.4.3-4. Summary of tests in pitting corrosion study

Test title	Abbreviated description of test method	Relevant parameters
<ul style="list-style-type: none"> Potentiodynamic polarization 	<ul style="list-style-type: none"> Measure current response of specimen during dynamic anodic and cathodic polarization in the expected aqueous environment 	<ul style="list-style-type: none"> Pitting potential Corrosion potential
<ul style="list-style-type: none"> Corrosion monitoring 	<ul style="list-style-type: none"> Measure the corrosion potential and the polarization resistance of specimens as a function of time in the expected aqueous environment 	<ul style="list-style-type: none"> Corrosion potential
<ul style="list-style-type: none"> Pit growth kinetics 	<ul style="list-style-type: none"> Measure the time for penetration of thin-walled specimens of various thicknesses during aqueous exposure under controlled potential conditions 	<ul style="list-style-type: none"> Pitting corrosion penetration Pitting correlation coefficients Pitting corrosion protection potential

PST87-2005-8.3.4-20

Test variables examined will be temperature, groundwater and vapor phase composition, filler and packing material composition, container materials composition, effects of fabrication and closure methods, variable surface effects (such as finish or scale), irradiation, electrochemical potential, and time. Tests conducted previously (Section 7.4.3) will be addressed and duplicated if deemed appropriate.

The study will be described in greater detail in the Container Materials Testing: Pitting Corrosion Study Plan (Fish, 1987).

8.3.4.3.4.3.3 Environmentally assisted cracking study.

The pertinent information need for this study is environmentally assisted cracking, with a performance parameter of environmentally assisted cracking susceptibility. A rate or penetration amount is not appropriate for this form of corrosion as its incubation times and rates are not amenable to long-term prediction. Thus, the goal will be to demonstrate that regions for environmentally assisted cracking susceptibility will not coincide with the expected repository environment.

The objective of the study is to determine the susceptibility of container materials to environmentally assisted cracking, which results in cracking and penetration of materials by simultaneous action of a tensile stress and aggressive chemical species. Testing for environmentally assisted cracking will be performed in the range of environments from nominal to the expected bounding conditions, with sufficient numbers of specimens to ensure that no significant regions of environmental parameters are unexplored. Environmental parameters will be chosen from groundwater measurements and projections of expected changes in the environment as a function of time and effects of repository construction and waste emplacement. An additional objective is to aid in the formulation of a behavioral description of environmentally assisted cracking processes and mechanisms for potential cracking of container materials in the repository environment. A further objective is to provide corrosion product information to the general corrosion study.

The study will result in a behavioral description that will focus on the processes relevant to environmentally assisted cracking in the expected repository environment. It will include effects of predicted container stresses and flows. It will address predicted threshold stress intensities (stress modified for effects of material flaws) for environmentally assisted cracking and compare such threshold stress intensities with predicted design stresses and flows. The persistence of relevant processes over the containment and controlled release period will be included, as well as estimates of rates of processes.

Results of the study will be communicated to waste package modeling activities. The results will be used as applicable in probabilistic lifetime models to demonstrate the probability of occurrence of this degradation mode in a final reference container material in the expected repository environment. This mode must be shown to be unanticipated with the final reference material and design to have a viable reference container material. The study will guide design efforts in choices of container material and closure method and possible choices in filler and packing material.

Test methods will use precracked, fracture-mechanics-type specimens under static and cyclic loading. Precracked specimens will be used to provide easy initiation points for environmentally assisted cracking to shorten the process of actual crack incubation (were it to occur) as a measure of conservatism. Both static and cyclic loads will be used on precracked specimens. Static loads will be used to closely simulate actual repository loading while cyclic loading will be used to provide more conservative threshold stresses. Slow strain rate tests will also be used as a rapid, conservative, but less qualitative method of assessing environmentally assisted cracking susceptibility; response to fracture mechanics testing will be relied on for more quantitative assessments of susceptibility. The copper materials are too plastic to be amenable to linear elastic fracture mechanics testing at all expected temperatures after waste emplacement. Therefore, slow strain rate testing will be relied on as a less quantitative but still very conservative means of assessing environmentally assisted cracking susceptibility in these materials. Usage of non-linear fracture mechanics concepts (the J-integral approach) will be explored also. Corrosion product analyses and solution chemistry analyses will also be performed to aid in characterizing corrosion processes. Table 8.3.4.3-5 describes the tests and parameters for the study.

Table 8.3.4.3-5. Summary of tests in environmentally assisted cracking study

Test title	Abbreviated description of test method	Relevant parameters
• Static load fracture mechanics	• Measure crack growth resulting from applied static stress and environmental interaction in precracked specimens exposed to simulated repository environments	<ul style="list-style-type: none"> • Environmentally assisted cracking threshold stress intensity factor • Crack propagation rate • Applied stress intensity factor
• Cyclic load fracture mechanics	• Measure crack growth resulting from applied cyclic loading and environmental interaction in specimens	<ul style="list-style-type: none"> • Environmentally assisted cracking threshold stress intensity factor • Crack propagation rate • Applied stress intensity factor • Cyclic frequency • Stress ratio
• Slow strain rate	• Measure ductility and fracture mode changes as a function of strain rate on tensile specimens in simulated repository environments	<ul style="list-style-type: none"> • Strain rate • Ductility • Fracture mode

PST87-2005-8.3.4-21

The data from the fracture mechanics tests will be used to predict a threshold stress intensity factor by analysis of crack growth rates as a function of applied stress intensity and the environment. The growth rates attributed to environmental enhancement will be analyzed with regression curve fitting and confidence parameters for the curves. The point where environmental enhancement of crack growth under cyclic loading ceases will be considered the threshold stress intensity. Service stress intensities will be compared to the threshold and must be shown to be significantly lower for freedom from environmentally assisted cracking to be ensured.

The data from slow strain rate tests will be used to characterize combinations of environment and material to determine if the combinations corresponding to potential prototypic repository conditions are free from environmentally assisted cracking effects. The criterion for the occurrence of EAC will be brittle features on the specimen fracture surface, which can be attributed to anodic stress corrosion or hydrogen embrittlement. Cracking evidence on fracture surfaces will be cause for rejection of a material, unless it can be clearly shown that service stresses will be below a credible threshold for environmentally assisted cracking.

Test variables examined will be temperature, groundwater and vapor phase composition, filler and packing material composition, container material composition, effects of fabrication and closure methods, variable surface effects (such as finish or scale), irradiation, strain rate, loading (including cyclic loading variables), electrochemical potential, and time.

The study will be described in greater detail in the Container Materials Testing: Environmentally Assisted Cracking Study Plan (Duncan, 1987a).

8.3.4.3.4.3.4 Crevice corrosion study.

The pertinent information need for this study is localized corrosion, with a performance parameter of maximum localized corrosion penetration in 1,000 yr. The ability to meet the parameter goal will be addressed through laboratory testing and theoretical studies leading to empirical corrosion rates and ultimately to mathematical predictive models based on mass transport/mechanistic considerations.

The objective of the crevice corrosion study will be to determine if crevice corrosion will occur in the candidate container materials in a basalt repository environment and, if crevice corrosion is found to be possible, to determine the expected corrosion rates. Crevice corrosion occurs as the result of differential electrochemical potentials caused by water chemistry variations in or near an occluded region or crevice.

A behavioral description of the processes and mechanisms anticipated and observed for crevice corrosion will be formulated, including estimated rates of processes. The study will provide support to the mechanistic corrosion model being developed within the waste package modeling program (Section 8.3.4.5). This model is based on transport limitations of available reactants and is expected to provide bounding predictions of corrosion rates for localized corrosion modes such as crevice corrosion.

The tests used to study crevice corrosion of container materials are conceptually the same as those used for pitting corrosion with modifications of the specimen design. Polarization curve tests will be conducted on specimens with artificial crevices to assess the electrochemical potentials required to initiate crevice corrosion, in order to determine if crevice corrosion can occur in the expected waste package environment. Crevice corrosion kinetics tests will be conducted to evaluate the rates of crevice corrosion penetration if it were to occur. Finally, corrosion monitoring tests using specimens with artificial crevices will be performed to evaluate the tendency for crevice corrosion potential, pH, and corrosion currents to change over long periods of time (at least 10 yr) toward conditions that would induce crevice corrosion.

Test variables to be investigated will include temperature, groundwater and vapor phase composition, filler and packing material composition, container material composition, effects of fabrication and closure methods, variable surface effects (such as finish or scale), irradiation, electrochemical potential, crevice geometry, and time. Table 8.3.4.3-6 summarizes the tests to be used in this study and lists the parameters to be generated.

The study will be described in greater detail in Fish (1987).

8.3.4.3.4.3.5 Mechanical and physical properties study.

The pertinent information needs for this study are mechanical and physical properties, with performance parameters of (1) creep rupture strength for container life, (2) buckling load, and (3) threshold for cracking propagation. The ability to meet the parameter goal will be addressed through laboratory testing and modeling of material response to expected loading and flaw cases.

Table 8.3.4.3-6. Summary of tests in crevice corrosion study

Test title	Abbreviated description of test method	Relevant parameters
• Potentiodynamic polarization	• Measure current response of specimens with artificial crevices during dynamic anodic and cathodic polarization in the expected aqueous environment	• Initiation potential • Corrosion potential
• Crevice corrosion monitoring	• Measure the corrosion potential, pH (inside crevice), and the crevice (galvanic) corrosion current of artificial crevice specimens as a function of time in the expected aqueous environment	• Crevice potential • Crevice corrosion penetration
• Crevice corrosion kinetics	• Measure the time for penetration of thin-walled specimens with artificial crevices under controlled crevice potentials during exposure to expected aqueous conditions	• Crevice corrosion correlation coefficients • Crevice corrosion penetration • Crevice corrosion protection potential

PST87-2005-8.3.4-22

The objective of the study will be to determine and document physical and mechanical properties of waste package materials in a detailed and rigorous fashion for use by the waste package materials and interaction testing program (Section 8.3.4.3), the waste package design development program (Section 8.3.4.4), and the waste package modeling program (Section 8.3.4.5). The properties will be those not generated routinely as part of existing testing or analyses but necessary for analyses within the programs or to demonstrate that a material will meet performance or design requirements such as the container design and construction standard activity.

The activities of this study may consist of documentation of properties from various existing literature sources or actual testing to directly determine the properties. Examples of properties that are candidates for study are the following:

- Tensile properties (yield and ultimate strength, uniform and final elongation).
- Creep properties (primary and secondary creep rates, rupture strain, and times).
- Toughness (fracture mechanics approach using K_{IC} or J_{IC} and ductile-brittle transition measurements for ferrous materials).
- Thermal conductivity.
- Residual stress measurements or analytical estimates.
- Thermal expansion.

In some cases, the properties may be determined from existing literature and data rather than experimental measurement. The time and temperature dependencies of the mechanical properties are of great significance, due to the necessity of prediction of properties throughout the containment and gradual release period.

As the scope of this study has not been defined, a table for tests and parameters is not given. The study will be described in greater detail in the Container Material Testing: Mechanical and Physical Properties Study Plan (Duncan, 1987b).

8.3.4.3.4.4 Application of Results

The corrosion behavior information will be used in the performance assessment investigations as described in Sections 8.3.4.5 and 8.3.5.

The following investigations of the waste package modeling program will employ the corrosion behavior information: performance sensitivity (Section 8.3.4.5.3), performance and reliability (Section 8.3.4.5.4), and model validation (Section 8.3.4.5.6).

The performance sensitivity investigation will examine the sensitivity of container lifetimes to variations in material properties through empirical corrosion behavior models during advanced conceptual design and through models incorporating empirical behavior and mechanistic relationships during license application design. The performance and reliability investigation will examine the variability of corrosion model coefficients, along with other parameters, in order to predict the statistical distribution of container lifetime and to develop a probability distribution function. The model validation investigation will benchmark, verify, and validate the empirical/mechanistic corrosion model mentioned previously. This will be continual, iterative examination of current results of laboratory- and engineering-scale corrosion tests.

Corrosion product information will be used in the waste package materials and interaction program (Section 8.3.4.3) and the waste package radionuclide behavior investigation (Section 8.3.4.3.6) to assess radionuclide release rate limits. The identify and form of corrosion products are necessary for the investigation to calculate sorption, diffusivity, and porosity of corrosion products. This information is needed to estimate radionuclide transport and retardation factors.

Corrosion behavior information and mechanical and physical properties information will be used in the waste package design development program (Section 8.3.4.4) in several areas. The qualification testing investigation (Section 8.3.4.4.6) will use laboratory corrosion results in design of the engineering-scale test system and its corrosion test systems. As corrosion data are available from qualification testing during license application design, they will be compared with data from laboratory-scale testing to ensure that assumptions of important corrosion phenomena and rates are correct. Both the qualification testing (Section 8.3.4.4.7) and container materials investigations (Section 8.3.4.3.4) may be modified, depending on results and comparisons. Another area of the design effort that will require corrosion behavior information and mechanical and physical properties information is the container development investigation (Section 8.3.4.4.5), which will be responsible for choice of container dimensions, including corrosion allowances as part of container design. The container materials investigation (Section 8.3.4.3.4) will provide corrosion rate information and estimates of confidence of corrosion during the container lifetime, which will be used in determining a corrosion allowance with appropriate margins of safety.

8.3.4.3.4.5 Schedule and Milestones

The schedule of the container materials investigation is given in Figure 8.3.4.3-4. The investigation is composed of five studies. Two milestones are given for the studies. Milestone No. 1 is a recommendation for a reference and alternate container material, to occur at the 30% advanced conceptual design point. This will constrain further testing and analysis to two materials. Milestone No. 2 is a recommendation for a final reference material at the beginning of license application design. This will constrain further testing and analysis to one material.

ACTIVITY	TIME									
GENERAL CORROSION				▽ ¹			▽ ²			
PITTING CORROSION				▽ ¹			▽ ²			
ENVIRONMENTALLY ASSISTED CRACKING				▽ ¹			▽ ²			
CREVICE CORROSION							▽ ²			
MECHANICAL AND PHYSICAL PROPERTIES							▽ ²			

PS60-2014-8.3.4-5

▽¹ RECOMMENDATION FOR REFERENCE AND ALTERNATE CONTAINER MATERIAL

▽² RECOMMENDATION FOR FINAL REFERENCE MATERIAL

Figure 8.3.4.3-4. Container materials investigation. .

8.3.4.3.5 Packing materials investigation

The packing materials investigation described in this section will provide data necessary to satisfy two information needs initially identified in Section 7.5 and further discussed in issue resolution strategies for Issues 1.4 and 1.5 (Sections 8.2.2.1.4 and 8.2.2.1.5). These information needs include waste package chemical stability and waste package physical properties and processes. These information needs are addressed by individual studies described in Section 8.3.4.3.5.3. The results of these studies will assist in meeting the NRC requirements applied to the waste package and engineered barriers systems.

8.3.4.3.5.1 Purpose and objectives

The purposes of the packing materials testing investigation are to obtain laboratory data that can be used to (1) describe the time-dependent properties and behavior of packing material in the waste package environment and (2) assess the sufficiency of packing to perform its assigned functions. Fundamentally, these functions are to enhance the stability of the container and to limit radionuclide mobility to the extent possible. The information obtained in this investigation will include data on the chemical stability and physical properties of packing and data on the processes occurring in packing. The chemical stability data will be used to predict the effects of chemical alterations of packing on container corrosion and on radionuclide behavior. The chemical stability data will also be used to predict the changes in physical properties that will occur in packing with time because of chemical alteration. Physical property data will also be used for (1) design calculations that predict the physical configuration of the waste package over time; (2) conceptual models of physical and chemical processes affecting packing and waste package performance; and (3) input to performance assessment models used to predict radionuclide transport and release from the waste package.

8.3.4.3.5.2 Rationale

The underlying rationale for investigating packing material properties is that the packing component is required to assist in meeting the NRC requirements applied to the waste package and engineered barriers systems. These include substantially complete containment of radionuclides in the waste package for 300 to 1,000 yr, addressed by Issue 1.4, and gradual release of radionuclides from the engineered barriers system thereafter (e.g., for approximately 10,000 yr), covered under Issue 1.5. Packing material will limit container degradation and radionuclide release over this time period by two distinct mechanisms: (1) by providing a low permeability porous medium surrounding the waste package, thereby limiting the flow rate of groundwater through the waste package; and (2) by establishing and maintaining a reducing environment that will minimize container corrosion and radionuclide solubilities. Packing also serves as a structural member of the waste package in supporting the container and distributing rock loads.

8.3.4.3.5.2.1 Relationship between input and performance measures.

The chemical stability data for the packing material (alteration products and altered groundwater chemistry, primarily) provide supporting information which is necessary to adequately characterize and extrapolate the ability of packing to satisfy the goals associated with the performance measures in Tables 8.2.2.1.4-1 and 8.2.2.1.5-1 and the related performance parameters in Tables 8.2.2.1.4-2 and 8.2.2.1.5-2.

In particular, the chemical stability data indicate whether packing can condition the groundwater through chemical reaction so corrosion of the container and radionuclide mobility are minimized. For container corrosion, the necessary groundwater characteristics include low redox potential, a moderately alkaline pH, and low concentrations of corrosive aqueous species (e.g., sulfide and chloride). For radionuclide mobility, necessary groundwater characteristics are low redox capacity, moderately alkaline pH, and low concentrations of radionuclide complexing species (e.g., carbonate, organics). If the chemical stability data indicate that such conditions are not achieved with the present packing composition of basalt and bentonite, then other packing components can be identified that will provide the necessary groundwater characteristics. The relationship between these data and the performance parameters are as follows:

- Redox condition--The ability of the packing to reduce the oxidation state of radionuclides and reduce corrosion depends on its ability to create a reducing aqueous environment. The potential for oxidation during the repository lifetime includes (1) partial oxidation of basalt via interaction with hot oxygenated air during the operations period, (2) hydrothermal interaction with oxygenated groundwater immediately following resaturation, and (3) hydrothermal interaction with oxidized radiolytic species throughout the remainder of the containment and gradual release period. Measurement of groundwater redox characteristics (e.g., oxygen content, Eh measurements, redox couples) and the identification of redox sensitive alteration products (e.g., magnetite versus hematite formation) indicate the tendency of the packing-groundwater system to become reducing.
- Distribution coefficient: distribution equation--The hydrothermal alteration of packing material to secondary phases will change the sorption reactions with radionuclides and possibly the sorption capacity of the packing. Identification of these secondary phases is needed to perform a small number of sorption experiments with important radionuclides and to assess the significance of the change in sorption behavior relative to control of radionuclide release from the engineered barriers system.

- Hydraulic conductivity--Three alteration processes have the potential to increase packing hydraulic conductivity (dehydration, steam treatment, and hydrothermal alteration). Data are required to determine the conditions under which an unacceptable increase in hydraulic conductivity occurs. These conditions will be compared with those predicted to occur during repository lifetime to determine if packing permeability will be acceptable.
- Diffusion coefficients--Alteration of packing may affect the physical component of diffusion coefficients by changing the effective path length through packing (e.g., tortuosity factor). Packing may also affect the chemical component of diffusion coefficients by changing the sorption reactions (see discussion for Distribution coefficient: distribution equation). Measurement and (or) estimates of diffusion coefficients in packing material are necessary for input into mass transport models that predict radionuclide release from the waste package and engineered barriers systems.
- Shear strength and creep rate--Hydrothermal alteration of packing may break down basalt particles whose spatial geometry determines the strength properties of packing. Identification of alteration phases and measurement of strength and (or) creep properties of altered packing are necessary to predict the movement of packing and container over the repository lifetime. Such displacement could also adversely affect the hydraulic conductivity of the packing material.

Another process that may influence packing chemical stability and groundwater composition is the formation of salts near the waste package during a boiling stage in the resaturation process. The potential for boiling and salt deposition will be studied as part of the investigation discussed in Section 8.3.4.2.3 where analyses are planned to estimate the severity of the reaction. A decision to do tests with packing will be made on the basis of these analyses.

The physical property data collected in the physical properties study (Section 8.3.4.3.5.3.2) will directly measure the physical property performance parameters and will be input to mass transport codes that predict radionuclide release. These include hydraulic conductivity measurements, diffusion coefficients, and strength/creep properties. The goals to be met for these properties are less than 10^{-6} cm/s for hydraulic conductivity and less than 10^{-5} cm²/s for diffusion coefficients of nonsorbing radionuclides. The goal for displacement over 10,000 yr is to allow no more than 50% reduction in packing thickness over that time period. Decrease in thickness will be calculated on the basis of the strength and creep estimates provided by physical property studies.

Other physical properties or processes that do not directly quantify but support the determination of performance parameters include resaturation time, swelling pressure, the effects of cementitious materials, and thermal conductivity. The relationship of these types of data to performance parameters are as follows:

- Estimates of resaturation time are necessary to evaluate temperature-moisture content history that packing and container will undergo during the repository lifetime. Packing performance will be affected by the influence of dehydration, steam treatment, and hydrothermal alteration on packing permeability (the performance parameter, hydraulic conductivity). It is not expected that packing will significantly delay resaturation, but estimates of time and temperature over which these processes will occur are necessary to evaluate the effects of resaturation on packing chemical and physical processes. Container performance will also be affected by these periods in terms of the corrosion modes and corrosion rates that in turn determine container lifetime (the container corrosion performance parameters). These periods will be quantified by the resaturation estimates. Data for these estimates will be partially satisfied under this investigation by experiments that measure resaturation of packing under a variety of repository relevant conditions. Other data will be supplied from mass transport studies that predict moisture flow in a repository system.
- Swelling pressure data are necessary to support packing permeability estimates (the performance parameter, hydraulic conductivity) because permeability is influenced by bentonite swelling and must be sufficient to fill voids left by emplacement configuration or dehydration following emplacement. These data are also used in prediction of container loading and structural analyses.
- Cementitious materials (i.e., materials whose primary component is portland cement) may influence packing performance by reacting with groundwater and increasing the calcium content and pH of the groundwater. This reaction could have the effect of reducing the swelling capacity of bentonite and increasing the permeability of packing. Therefore, the data produced to quantify these effects support the performance parameter, hydraulic conductivity.
- Thermal conductivity measurements generally support all performance parameters dealing with packing physical and chemical properties as well as those related to container lifetime because these data are needed to calculate thermal waste package profiles. The temperature estimates are fundamental for identifying the appropriate laboratory conditions for gathering data and for predicting container lifetime, packing permeability, packing chemical alteration, and radionuclide behavior.

Additional information that must be gathered in support of the testing data described above are an evaluation of the natural variability in composition of presently proposed packing materials (i.e., sodium bentonite) and evaluation of other potential packing materials that may provide more reliable performance of packing functions. With regard to natural variability, sodium bentonite is made up primarily of sodium montmorillonite with additional minor phases including salts, sulfides, sulfates, organics, and other silicates. These phases can interact with groundwater and potentially increase corrosion or radionuclide mobility. Therefore, given the large amounts of material needed in the repository, an evaluation, primarily through literature search, is necessary to determine if (1) further testing is required; (2) pretreatments of packing material will be needed prior to emplacement to remove harmful minor components; (3) other design options need to be pursued to reduce uncertainty in performance estimates; or (4) other, more stable materials need to be substituted for current materials in order to make packing materials perform their functions acceptably. Similar evaluations are also necessary for other potential packing components.

8.3.4.3.5.2.2 Data input and technical concerns.

Current data input about the two mechanisms cited above that will limit container degradation and radionuclide release involve information on chemical stability, and physical properties and processes. The data provided by these information needs are briefly described in Table 8.3.4.3-7. The chemical stability data will be provided by the chemical stability study. Data on transport properties, mechanical strength, and temperature history will be provided by the physical properties study. Information needs are shown in Table 8.3.4.3-7 along with the proposed application of these data to the resolution of Issues 1.4, 1.5, and 1.10 and the associated technical concerns (see Section 7.5.3). These interrelationships are briefly summarized below.

The primary data to be provided in the chemical stability study are the changes in packing material mineralogy and groundwater chemistry resulting from dehydration, steam treatment, and hydrothermal alteration. These data are inputs to the resolution of technical concerns in the following manner:

- Quantification of redox reaction rates and reduction capacity in the waste package and engineered barrier system. Packing is composed partially of crushed basalt, which is a primary reductant in the engineered barriers subsystem. Observation of characteristics of iron-bearing secondary minerals and redox sensitive groundwater characteristics (e.g., oxygen content, aqueous redox couples such as sulfate-sulfide) in hydrothermal and basalt-vapor interaction experiments involving packing and groundwater provide an indication of redox reactions in packing. These data are combined with more direct evidence of redox effects on container corrosion (i.e., corrosion experiments in the presence of packing) and radionuclide behavior (i.e., sorption/solubility experiments with radionuclide-doped groundwater and packing or basalt) to determine whether the redox reaction rates and capacity of packing are sufficient to establish or maintain reducing conditions that limit container corrosion and radionuclide solubility.

Table 8.3.4.3-7. Information needs to be satisfied by packing materials investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant issues
Title	Abbreviated description		
Chemical stability	Solid alteration products (resulting from dehydration steam treatment and hydrothermal alteration) and groundwater chemistry changes resulting from hydrothermal alteration	These data will be used to characterize the long-term geochemical environment in the waste package. Observed changes in mineralogy and groundwater will be compared to natural analog data and thermodynamic equilibrium predictions to limit the range of geochemical conditions expected to occur. The effects of the ranges of performance related physical and chemical properties of packing will be tested to the extent possible and packing performance will be evaluated on the basis of that data	Issues 1.4 and 1.5
Physical properties and processes	Hydraulic conductivity, swelling pressure, diffusion coefficients, resaturation rate, hydraulic conductivity as affected by cementitious effects	These data will be used to characterize mass transport of aqueous species and radionuclides through packing. The hydraulic conductivity and swelling pressure data are used to demonstrate that advective processes are insignificant and diffusion dominates mass transport. Diffusion coefficients are direct inputs to mass transport models which predict radionuclide release and some types of corrosion rates.	Issues 1.4, 1.5, and 1.10
	Shear strength, creep properties, consolidation coefficients	Container lifetime predictions will be based partially on mechanistic container failure models including loading and deformation. Packing material shear strength, creep properties, and consolidation coefficients are required as inputs to these models.	Issues 1.4, 1.5, and 1.10
	Thermal conductivity heat capacity	Temperature affects all physicochemical properties and reactions in a repository environment. To calculate thermal profiles as a function of time in the waste package and engineered barrier system packing thermal conductivity values are required as input.	

PST87-2005-8.3.4-24

- Satisfactory long-term predictions of container lifetime and corrosion behavior. The most important data to be provided are the time-dependent characteristics of groundwater composition resulting from hydrothermal interaction with packing that could influence corrosion processes and rates (e.g., pH, corrosive species such as oxygen and sulfate). These data provide a range of groundwater characteristics expected to occur over the repository lifetime and enhance the predictability of the corrosion environment over the repository lifetime. This improved predictability, in turn, improves confidence in the container lifetime estimates.
- Satisfactory justification of long-term predictions of packing properties on the basis of short-term data. Short-term chemical stability data, primarily the effects of hydrothermal alteration on packing mineralogy and groundwater characteristics provide a useful starting point for predicting the expected ranges of these characteristics. When combined with appropriate natural analog data (e.g., hydrothermal Iceland basalt system) and thermodynamic estimates of equilibrium solid and solution characteristics, a probable range of conditions can be quantified and the influence of these changes in physical properties and chemical interactions with radionuclides can be assessed experimentally and theoretically.
- Determination of the capacity of steam to increase the permeability of packing to an unacceptable value. Data to be obtained will provide the direct experimental data that measures the change in packing permeability and swelling pressure as a function of vapor flow, temperature, and moisture content. If possible, data will also be obtained to explain the process that causes steam to inhibit bentonite swelling capacity. Comparison of the conditions under which steam causes unacceptable packing permeability increases with those estimated to occur in the waste package in the repository will be used to determine if steam effects significantly degrade packing performance.
- Demonstration of the ability of packing to prevent significant container subsidence over the repository lifetime. The change in packing particle size, particularly basalt, due to hydrothermal alteration may influence consolidation and creep characteristics. These data provide supporting information that can be used to calculate the extent of additional consolidation or creep expected to occur resulting from the change in particle size, particle configuration, and compositional change.

The primary transport properties data to be provided are the physical and physicochemical properties of packing that influence mass transport. Mass transport processes affect both container corrosion and radionuclide mobility.

Properties quantified include hydraulic conductivity, swelling capacity, diffusion coefficients, resaturation rates, and hydraulic conductivity as affected by cementitious effects. In addition, packing resaturation data will be provided. These data are input to the resolution of technical concerns derived from Issues 1.4 and 1.5 in the following manner:

- Quantification of the waste package resaturation process in the repository to provide limits on temperature-time-moisture content profiles. These data will quantify the conditions under which resaturation will occur and the rates of resaturation as affected by independent variables. These data, combined with large-scale resaturation test data and resaturation analyses, will provide useable temperature-time-moisture content relationships needed for all waste package and engineered barriers system performance analyses.
- Satisfactory long-term predictions of container lifetime and corrosion processes. Mass transport of aqueous species in ground-water that surrounds and flows past the container will affect corrosion processes. Both hydraulic conductivity data and diffusion coefficient data will be used to predict corrosion rates, particularly if either the flux of the corrosive agent past the container surface or the transport of corrosion products away from the container surface is the corrosion rate limiting reaction.
- Satisfactory justification of long-term predictions of packing properties on the basis of short-term data. Data will provide direct measurement of the properties of interest (e.g., hydraulic conductivity, swelling pressure, diffusion coefficients) and generate data from a test matrix designed to cover the range of pertinent repository conditions. An estimate of the range of values for these properties then can be made for the span of the repository lifetime. From this estimate, the performance of packing can be evaluated relative to its ability to assist in meeting the regulatory requirements.
- Determination of the effects on packing permeability resulting from reactions of groundwater with cementitious repository structural materials and subsequent interaction of that groundwater with packing. Data will provide direct measurement of the changes in groundwater following interaction with cementitious materials and the influence of that groundwater on bentonite swelling pressure and packing permeability. The duration of groundwater alteration by cementitious materials will also be tested because the influence of cement-groundwater interactions on groundwater composition are not expected to last for a long time relative to repository history. This will be done to evaluate the potential for such altered groundwater to come in contact with packing. If altered groundwater is shown not to come in contact with packing, the concern will be resolved. The occurrence of bentonitic rocks cemented by calcite may also be investigated as a natural analog.

The primary mechanical properties data to be provided are the strength and creep properties of packing that determine the ability of packing to provide sufficient container support. These data provide direct measurements of these properties necessary to demonstrate the ability of packing to prevent significant container subsidence over the repository lifetime and to mitigate stress applied by rock load or rock creep. This analysis will be completed using the strength property data and a mechanical strength analysis.

The primary temperature history data to be provided are the thermal conductivity and heat capacity of packing material. These data support all of the technical concerns in Issues 1.4 and 1.5 because all concerns require an estimate of temperature history (and temperature ranges) in the waste package and engineered barriers systems to support a test matrix and associated performance analyses, which use the data generated. In general, temperature is the most significant variable parameter that influences material properties and physicochemical processes.

8.3.4.3.5.2.3 Constraints.

Constraints that exist for this investigation are time, closed versus open systems, spatial geometry, and environment. The first constraint on most experimental systems is the inability to perform experiments over time periods long enough to simulate the repository time scale. For example, silicate reaction kinetics are quite slow relative to a laboratory time scale of a few years at most. Consequently, metastable phases are likely to form in laboratory experiments without ever evolving to an equilibrium phase assemblage. This constraint is being addressed by the natural analog study (see Section 8.3.4.2.4.3.1), which characterize alteration products produced on a geologic time scale under conditions similar to those expected to occur in the repository environment. Comparison of these alteration products with those produced in laboratory experiments will provide an indication of how different packing properties could be affected by long-term hydrothermal processes. Also, a decision can be made about the degree of relevance of laboratory data to predict long-term packing behavior based on these comparisons.

The second constraint is that the experimental systems are primarily closed systems. In the real environment, of course, the waste package system will be open continuously to mass transport, which may have an effect on hydrothermal reactions. It is possible to add water to Dickson-type autoclaves in discrete volumes or to flowthrough autoclaves and permeameters so that the system is not completely closed. However, this approach may not be truly representative of the repository system. The flowthrough systems allow a more accurate simulation of the real repository environment in terms of groundwater transport through the waste package and an open geochemical system, as long as the groundwater entering the system has been pretreated to simulate its reaction with components of the flow path leading to the waste package. Sufficiently low flow rates can be imposed if packing is used at its recommended density.

A constraint that is not easily overcome in laboratory-scale experiments is that of spatial geometry, which could primarily affect physical processes and properties. In particular, the particle mixing configuration and possible inhomogeneities in the borehole surface are difficult to simulate in laboratory-size permeameters and flowthrough autoclaves. Thus, possible effects of inhomogeneities of the packing material in an emplaced waste package cannot be reflected in laboratory experiments. These effects must be addressed by larger-scale (qualification) or field-scale testing.

Another constraint is that the maximum basalt particle size for laboratory tests is approximately 0.8 cm (0.3 in.) or less in size. Larger particle sizes may be considered for emplacement, which would require tests with those materials in larger scale testing equipment. To obtain altered packing material for other experiments or tests, particularly physical property tests, fresh packing will be altered in place (i.e., packed in a container, altered, then tested) to obtain, to the extent possible, representative changes in both the mineral assemblage and physical properties such as density and porosity.

The environmental constraint for experimental determination of many packing material properties is the difficulty in simulating the reducing environment after hydrothermal interaction of groundwater with packing has occurred. Contamination with oxygen is unavoidable during sample preparation. Artificial reduction of the system by the addition of a reducing agent such as hydrazine is of limited use because the effects of hydrazine on chemical reactions involving radionuclides are not well understood. A more acceptable method being used is to conduct the experiments in an anoxic environment and allow basalt/groundwater or basalt/bentonite/water reactions to naturally control the redox state of the system.

8.3.4.3.5.3 Description of studies

The studies described in the following two subsections are designed to satisfy the corresponding information needs identified in Section 7.5 and further discussed in issue resolution strategies for Issues 1.4 and 1.5 (Sections 8.2.2.1.4 and 8.2.2.1.5). The results of these studies will assist in meeting the NRC requirements applied to the waste package and engineered barrier system.

8.3.4.3.5.3.1 Chemical stability study.

The major data needs from the chemical stability study (alteration products and groundwater chemistry) provide an understanding of the long-term chemical changes that will occur in the packing material that may affect the physical properties of the packing material, radionuclide behavior in packing material, and container corrosion.

Effective prediction of long-term packing material performance is dependent on an understanding of chemical and physical reactions that may occur in the packing material exposed to the repository environment.

Alteration of the initial mineral assemblage could affect (1) physical properties and processes such as density, hydraulic conductivity, and rate of mass transport; and (2) chemical properties and processes such as redox buffering capacity and radionuclide precipitation/sorption reactions. A summary of the tests, methods, parameters evaluated, and data produced for the chemical stability study is given in Table 8.3.4.3-8. The data produced correspond to the parameters listed in Table 8.2.2.1.5-1. Each test is discussed in more detail below.

Hydrothermal tests are being completed under conditions (e.g., groundwater composition, temperature, pressure, and packing materials composition) relevant to a repository in basalt. The basic data to be acquired from these tests will be (1) changes in solution concentration as a function of time (where appropriate); (2) time required to reach the steady-state solution condition; and (3) identification of the solids and their composition before and after the experiment. A comparison of the phase assemblages before and after hydrothermal reaction will identify (1) the extent of initial packing materials phase alteration (i.e., the stability of the packing materials); (2) the packing materials alteration products; and (3) the likely effect of hydrothermal alteration on key packing materials properties (e.g., thermal and hydraulic conductivity, porosity, bulk density, groundwater buffering capacity, and sorptive capacity). These data, along with a study of natural mineral analogs of packing materials found in host rock and thermodynamic estimates of equilibrium conditions, will provide a reasonable estimate of potential packing material stability.

The intent of the flowthrough packing material hydrothermal test is similar to the closed-system tests in that solution data are gathered as a function of time and solids are analyzed following the experiment. However, the experimental system is devised so that simulated groundwater flows through the packing material continuously. Thus, a closer approach to a more realistic waste package environment is simulated.

The tests will be used primarily to determine the effect of flow on hydrothermal reactions. This will be done by comparing static versus flow-through alteration products. If flow does not change the chemical reactions in packing, then the static tests will be given more credence as a reasonable simulation of the packing material environment. Flowthrough tests will also provide a direct evaluation of hydrothermal reactions in the flowthrough environment on physical properties, particularly hydraulic conductivity, density, and porosity.

In a separate group of experiments, two types of pretest sample preparations will be conducted. First, packing material will be dehydrated at different temperatures up to 300 °C for periods of time up to a year or more. This sample preparation technique will be used to simulate the dehydration period that may occur shortly after waste emplacement because of radiogenic heating. Second, packing material will be exposed to steam at different temperatures up to 300 °C for periods of time up to a year or more. This technique will be used to simulate the steam environment that may exist in the waste package environment during the preclosure period.

Table 8.3.4.3-8. Summary of tests in packing materials
chemical stability study

Test title	Abbreviated description of test method	Relevant parameters
Hydrothermal reactions static	Dickson autoclaves and Parr vessels are used to contain packing/water samples at elevated temperature and pressure to accelerate the hydrothermal reactions that will occur in a waste package. The solids will be analyzed after termination of the experiment to determine the alteration products formed. Solutions will be sampled periodically during the run to determine chemical composition versus time.	Alteration products, groundwater composition, redox environment
Hydrothermal reactions dynamic	Flowthrough autoclaves are used to contain packing material samples at elevated temperature and pressure, while groundwater is pumped through the vessel. Effluent solution will be sampled constantly and analyzed for its chemical composition. Solids will be analyzed after termination of the experiment.	Alteration products, groundwater composition, redox environment
Dehydration	Dry packing samples in airtight containers will be placed in ovens at different temperatures. Samples will be removed periodically and tested to determine swelling pressure, hydraulic conductivity, and altered phases (if any).	Alteration products, hydraulic conductivity, swelling pressure
Steam	Static autoclaves will be used to contain samples of packing during exposure to steam in a stagnant atmosphere. Flowthrough autoclaves will be used to contain packing samples during exposure to flowing and stagnant steam. Samples of solids will be removed for determination of alteration phases. Swelling pressure and hydraulic conductivity measurements will be made in the flowthrough systems after exposure to steam.	Alteration products, swelling pressure, hydraulic conductivity, resaturation times
Gaseous oxidation	Static and flowthrough furnaces will be used to expose crushed basalt of varying surface area to volume ratios to appropriate gaseous mixtures (oxidized) that simulate the repository environment. Experiments will be performed at various temperatures. Oxidation of iron-bearing phases and changes in Fe (II)/Fe (III) ratios will be identified to estimate kinetics and extent of oxidation of packing prior to saturation.	Alteration products (iron-bearing) and changes in Fe (II)/Fe (III) ratios
Radiation	Static and dynamic autoclaves will be used to contain packing material samples during tests identical to those for steam, except that samples will also be exposed to the effects of gamma radiation during the steam treatment for some samples, while other samples will be exposed only to the radiation without the steam treatment. Samples will be tested for alteration phases, swelling pressure, and hydraulic conductivity.	Alteration products, swelling pressure, hydraulic conductivity

P5787-2005-8.3.4-25

Packing and basalt will also be exposed to the gaseous environment expected to occur in the repository prior to saturation. The basic data that will be acquired from these experiments are solids characterization that identify in particular the changes in (1) iron-rich basalt phases mineralogy, (2) solid ferrous to ferric ratios and (3) bentonite mineralogy. The changes in iron phase mineralogy and ferrous to ferric ratios will be used to estimate the degree of oxidation expected to occur in the basalt prior to resaturation. These data, when gathered as a function of temperature and surface area to volume ratio, will provide a means of estimating the kinetics of the oxidation reaction. This information, along with oxidation reactions under saturated condition, will provide a complete set of data for estimating the ability of packing to provide a reducing environment during the repository lifetime. Changes in bentonite composition, if any, along with the hydraulic conductivity and swelling capacity measurements provide information about the mechanism that causes the reduction in swelling capacity as a function of temperature and moisture content.

Dehydration tests are needed to determine the effect of dry heating on hydrated packing materials (e.g., bentonite and zeolites) that may occur shortly after waste emplacement. In particular, it is necessary to determine if dry heating causes irreversible changes in the crystalline structure of bentonite and zeolites, thereby causing a reduction in unit volume and loss of swelling capacity (in the case of bentonite). This information, in turn, will help demonstrate whether dehydration will cause a significant reduction in the ability of the packing materials to maintain a low-permeability medium following the dehydration period.

8.3.4.3.5.3.2 Physical properties and processes study.

Data on physical properties are needed primarily to understand and predict mass transport processes, which in turn have significant effects on container corrosion and radionuclide mobility. In addition, by determining packing material specifications (e.g., composition, density) at which acceptable physical property values are achieved, design specifications for packing material can be recommended.

Physical properties of a packing material can be engineered by changing composition, density, and particle size distribution to (1) retard ingress of groundwater to and control the flow of groundwater past the container during the repository containment period (300 to 1,000 yr) and (2) control the physical transport of radionuclides by groundwater. Protection of the container is most important during preclosure, decommissioning, and the containment part of the postclosure period when radionuclide isolation is most dependent on physical containment. Later in the postclosure period, emphasis is placed on the radionuclide isolation function of the packing. This is accomplished by the chemical reactivity of the packing material and host rock to control radionuclide release within required limits. The most effective method for accomplishing these requirements relative to physical processes is to limit groundwater flow per unit time through the waste package.

Consequently, the most important packing material physical properties in both instances are those that significantly affect groundwater movement through the waste package (e.g., hydraulic conductivity, density, swelling capacity, and shear strength). A summary of the tests, methods, parameters evaluated, and data produced for the physical properties and processes study is given in Table 8.3.4.3-9. More detailed discussions of each of the tests follow.

The hydraulic conductivity of the waste package packing materials is one of the key data requirements for waste package design and performance assessment. Hydraulic conductivity of packing material determines the attainable rate of advective and convective mass flux and, thus, is one of the rate-controlling parameters for radionuclide release from the waste package. If the hydraulic conductivity is below some maximum value, then diffusion becomes the rate-controlling process relative to convection, and the mass flux is minimized. Therefore, a sufficiently low hydraulic conductivity value for packing material will (1) minimize the mass flux of corrosive aqueous species to the waste container, (2) maximize residence time for the radionuclides in the packing materials to complete sorption/precipitation reactions, and (3) maintain diffusional control of radionuclide transport through the packing material. The current data base suggests that hydraulic conductivity values are most influenced by the density and composition of the packing materials and temperature of the saturated packing materials. Consequently, a series of tests is being completed that measures hydraulic conductivity as a function of these parameters. These data will enable the waste package designer to specify density and composition of packing material, which are required to ensure that the hydraulic conductivity of the packing material falls below the maximum permissible value to maintain diffusional radionuclide transport.

The swelling of the packing materials in a confined volume (e.g., constrained by the borehole wall) is a desirable property for the packing material component. Following emplacement, a period of dehydration may occur in the packing materials prior to saturation, which may result in the formation of cracks. In addition, minor void spaces will exist in the packing materials created by the emplacement process (e.g., joints between precompressed blocks, tolerance gaps). The presence of bentonite is expected to eliminate the possibility of significant void space in the packing materials because it increases in volume on contact with water. In addition, bentonite will be sufficiently mobile to infiltrate a short distance into the fractures intersecting the borehole wall.

Similarly, a steam environment may also exist prior to resaturation. Recent work by Coture (1985) suggests that steam will react with bentonite and reduce its swelling capacity. Therefore, tests must be conducted to quantify the effects of dehydration and steam on swelling capacity. This information will be used to evaluate the effects of potential swelling reduction on the hydraulic conductivity of the packing material.

Table 8.3.4.3-9. Summary of tests in packing materials physical properties and processes study

Test title	Abbreviated description of test method	Relevant parameters
Hydraulic conductivity	Measure flow rate and hydraulic head loss from a permeameter filled with packing material.	Hydraulic conductivity (cm/s)
Swelling pressure	Measure pressure developed by water saturated packing in a high-pressure permeameter fitted with a load cell.	Swelling pressure (MPa)
Thermal conductivity	Thermal conductivity apparatus is used to measure heat flux through a sample under a known temperature gradient.	Thermal conductivity (W/(m °C))
Static diffusion/dispersion coefficient	Allow a radionuclide to diffuse into a sample of packing material, measure its concentration, and fit the data to a numerical model to extract the diffusion coefficient.	Diffusion coefficient (cm/s ²)
Dynamic diffusion/dispersion coefficient	Inject a radionuclide into an influent stream passing through a column packed with packing material, analyze the effluent for radionuclide content versus time, and fit the data to a numerical model to extract a diffusion coefficient.	Diffusion coefficient (cm/s ²)
Shear strength	The sample deformation rate is measured on samples of packing material in a triaxial cell with confining, pore, and back pressures. The pressures at which failures occur are analyzed to obtain Mohr circles (angle of friction and cohesion).	Shear strength (MPa), angle of friction, and cohesion (MPa)
Consolidation	A sample is placed in a consolidometer with a known axial load applied. The volume change versus pressure curve and hydraulic conductivity are measured to calculate coefficient of consolidation.	Consolidation coefficient (cm/s ²) and modulus of volume change (cm ³ /Pa)
Cementitious materials	A sample of cement is leached with groundwater and the leachate is used as influent to a swelling pressure permeameter. Swelling pressure and hydraulic conductivity will be measured as above and compared with results with normal groundwater.	Hydraulic conductivity (cm/s) and swelling pressure (MPa)

PST87-2005-8.3.4-26

Swelling pressure of the packing materials will be primarily a function of the packing materials density, bentonite content, and to a lesser extent, temperature. Therefore, a series of tests is being run to determine the swelling pressure for basalt/bentonite mixtures over a range of different densities and temperatures.

During the early part of the containment period following closure of the repository, high waste package temperatures (approximately 250 °C and low pressures (approximately 0.1 MPa (14.5 lbf/in²)) are expected to cause dehydration and (or) steam treatment of the hydrated packing material, particularly sodium bentonite. With time, the packing materials temperatures will drop and pressures will rise such that groundwater will be stable as a liquid phase in the packing material. Subsequently, a wetting front will develop in the packing material and saturation will occur. Determination through modeling analyses of the temperatures and pressures at which saturation will occur is needed to predict the maximum temperature at which waste package hydrothermal interactions (e.g., container corrosion, waste form dissolution, and radionuclide sorption/precipitation reactions) can be expected to occur.

The resaturation temperature is dependent on the vapor pressure that will exist in the packing materials as vapor moves through the packing materials. If vapor transport is sufficiently slow, vapor pressure will build up causing condensation and resaturation. Vapor transport rates will be affected by temperature and may be affected by packing materials composition, density, and spatial geometry.

The structural integrity of a packing material mix is important in that the packing material must provide sufficient bearing capacity to prevent container subsidence (current goal is no more than 50% reduction of packing thickness). Also, to evaluate the long-term bearing capacity of packing material, the potential for creep must be minimized. Packing material shear strength will vary with effective or intergranular pressure, density, particle interlocking, cohesion, water content, compaction technique, particle-size distribution, and component mixture ratios. The required shear strength of an unconfined packing material used in a horizontal container placement application is approximately 0.035 MPa (5.1 lbf/in²) based on the design weight and dimensions of the current defense high-level waste container (e.g., heaviest predicted waste package) (Westinghouse, 1982). Container settlement will be based primarily on the packing material emplacement density, moisture content, ratios of bentonite to basalt, and container weight. The data will be used to determine a packing material composition and density to provide the strength needed to support the container.

An adequate thermal conductivity for the packing material is required to keep waste package temperatures below 300 °C (Westinghouse, 1982) because thermal conductivity values determine the rate at which heat dissipates from the container. Thermal conductivity may vary as a function of temperature, density, composition, particle-size distribution, and moisture content. Consequently, thermal conductivity measurements on packing material must be performed to obtain input to thermal models that predict the thermal profiles of the waste package system.

The purpose of static diffusion tests is to determine the diffusion coefficients for radionuclides in the packing material. These coefficients are used to predict the radionuclide mass transport in the packing material when groundwater velocities are low enough to reduce advective transport to an insignificant level relative to diffusional transport to the accessible environment boundary. Diffusion coefficients are primary input to models that estimate the radionuclide transport and release from the waste package.

The purpose and objectives of flowthrough tests are similar to those of the static diffusion cell tests. The primary difference is that advective transport is included in the experimental system. Advection will be very low in this system because of low packing permeability. This manner of comparison of estimated diffusion coefficients between static and flowthrough experiments will demonstrate whether advective processes influence radionuclide transport. In addition, flowthrough experiments will be a more realistic simulation of the actual waste package environment by simulating an open rather than closed geochemical system.

8.3.4.3.5.4 Application of results

Results from the packing materials chemical stability study are to be used mainly for specifying starting materials and solution conditions (pH and elemental concentrations) for (1) the packing materials physical properties and processes study (Section 8.3.4.3.5.3.2), (2) the waste package radionuclide behavior investigation (Section 8.3.4.3.6), and (3) the container materials investigation (Section 8.3.4.3.4). The materials and groundwater chemical conditions must be understood for testing in these investigations to be meaningful and represent the waste package (i.e., reducing) environment.

Mechanical properties, specifically swelling pressure, shear strength, and consolidation measurements will be used by the container development investigation (Section 8.3.4.4.4) to calculate loading stresses on the container during the containment period. These data are needed for planning corrosion testing (Sections 8.3.4.3.4.3.1 and 8.3.4.4.6.3.1) and for estimating container lifetime (Sections 8.3.4.5.3.3.3 and 8.3.4.5.4.3.3) in the waste package modeling program.

Swelling pressure data on packing are also needed for the altered material that will be present after the containment period to ensure that packing will be capable of swelling into and filling fractures with low permeability material (to maintain diffusional control of radionuclide release).

Thermal conductivity data on packing under conditions that vary from dry to completely saturated are needed for the waste package modeling program (Section 8.3.4.5) to predict the thermal history of the waste package and repository.

Transport properties, mainly diffusion coefficients of radionuclides and corrosion products and hydraulic conductivities are needed to support the container development investigation (mechanistic corrosion model development) (Section 8.3.4.4.4) and the waste package modeling program (radionuclide release rate calculations) (Section 8.3.4.5). Hydraulic conductivity data are also needed for prediction of resaturation times in both the waste package modeling program and the qualification testing investigation (Section 8.3.4.4.6).

Colloid mobility data are needed for the waste package modeling program to aid in calculating radionuclide release rates for radionuclides that are either sorbed on or a component of mobile colloids in the waste package.

8.3.4.3.5.5 Schedule and milestones

The schedule for the packing materials investigation is given in Figure 8.3.4.3-5. Two milestones are given for the studies. Milestone No. 1 is a recommendation for a reference and alternate packing material to occur at the 30% advanced conceptual design point. Milestone No. 2 is a recommendation for a final reference material at the beginning of license application design.

8.3.4.3.6 Investigation of waste package radionuclide behavior

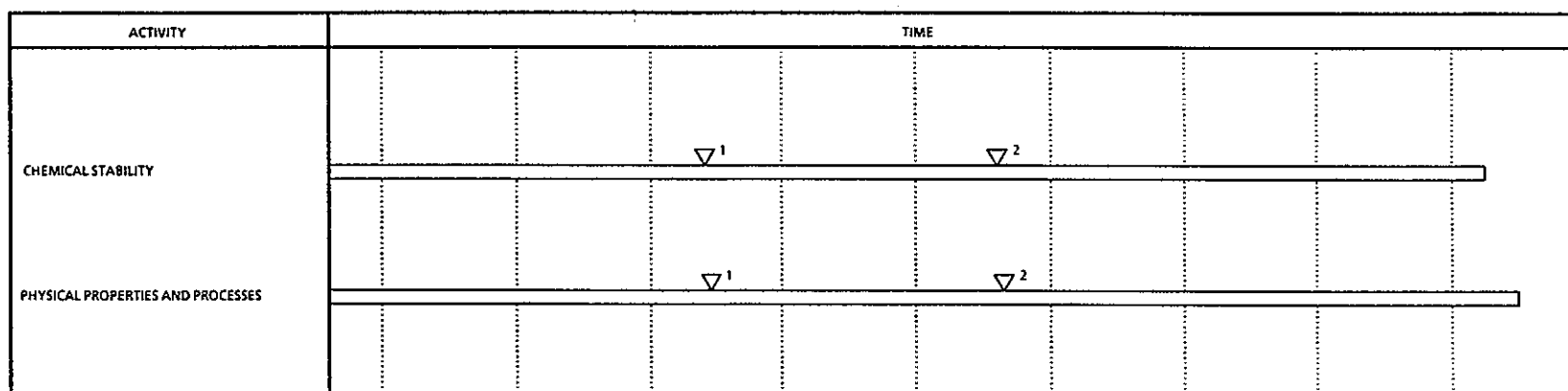
The radionuclide behavior investigation describes the studies necessary to acquire the data for evaluating the radionuclide release performance of the waste package over the performance life of the repository.

8.3.4.3.6.1 Purpose and objectives

The goal of the waste package radionuclide behavior investigation is to gather the necessary data to aid in the resolution of Issues 1.4 and 1.5 (see Section 8.2.2). Information provided by this investigation will be used to (1) develop radionuclide transport codes to model radionuclide releases from the waste package and (2) provide a source term to site-specific transport codes for the modeling radionuclide releases to the accessible environment. Such modeling efforts will be used as the basis for determining whether the engineered barriers subsystem will comply with 10 CFR 60.113 (NRC, 1987a) regulatory criteria.

The waste package radionuclide behavior investigation is based on four studies:

- Radionuclide solubility/sorption and speciation behavior.
- Waste/barrier/rock interactions: spent fuel release testing.



P588-2014-8.3.4.6

▽¹ RECOMMENDATION FOR REFERENCE AND ALTERNATE PACKING MATERIAL.

▽² RECOMMENDATION FOR REFERENCE MATERIAL.

Figure 8.3.4.3-5. Packing materials investigation.

- Waste/barrier/rock interactions: borosilicate glass release testing.
- Waste/barrier/rock interactions: other waste form testing.

Specific information provided by these studies includes (1) aqueous concentration limits for radionuclides (solubility limits), (2) identification and characterization of secondary phases that control aqueous radionuclide concentrations, (3) radionuclide sorption and speciation behavior, (4) effects of various physical properties and waste package components (and configurations) on radionuclide behavior, (5) compatibility of waste package components under simulated repository conditions, and (6) matrix dissolution behavior of spent fuel.

The above information is required to establish radionuclide behavior in the waste package environment in terms of (1) the aqueous concentration limits of key radionuclides, (2) the ratios of specific radionuclides to uranium in the spent fuel matrix and the aqueous phase, (3) the reduction of multivalent radionuclides, and (4) radionuclide distribution coefficients and distribution equations. The goal of the first performance parameter is a maximum (bounding) radionuclide concentration less than a specified value for a specific suite of radionuclides. This concentration is radionuclide-dependent and must be established with a high needed confidence. The goal of the second performance measure is for the ratio of a specific radionuclide to UO_2 in the spent fuel matrix to be essentially equivalent to the ratio of the same radionuclide to UO_2 in solution (i.e., the ratio of the ratios will be 1.0). This goal must be met with a to-be-determined needed confidence. The goals of the third and fourth performance parameters must be met with a high needed confidence and are radionuclide dependent. These performance parameters, performance goals, and needed confidences are summarized in Tables 8.2.2.1.4-3 and 8.2.2.1.5-3.

8.3.4.3.6.2 Rationale

The information needs addressed by this investigation are (1) radionuclide solubility, sorption, and speciation behavior, and (2) spent fuel matrix dissolution behavior. This information need supports the alternate technical strategy for resolution of Issues 1.4 and 1.5. Satisfying these information needs will allow radionuclide source terms to be established; these source terms are fundamental requirements of radionuclide transport and release modeling.

The above information needs are addressed in detail as Technical Concerns 7.5.3.5 and 7.5.3.6 in Section 7.5.3. A synopsis of these technical concerns is presented in Table 8.3.4.3-10. Technical Concern 7.5.3.5, entitled "Demonstrate Stoichiometric Dissolution Limits for Radionuclide Release," addresses spent fuel matrix dissolution behavior. If it can be

Table 8.3.4.3-10. Information needs to be satisfied by the waste package radionuclide behavior investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern
Title	Abbreviated description		
Radionuclide solubility/sorption and speciation behavior	<ul style="list-style-type: none"> Radionuclide solubility behavior: evaluate the effects of various waste package components on the solubility (and sorption) behavior of key radionuclides 	<ul style="list-style-type: none"> Show solubility limits for key radionuclides can be achieved from both undersaturation and oversaturation at repository-relevant experimental conditions. Identify and characterize solubility-controlling secondary phases. 	7.5.3.6 Demonstrate solubility limits for radionuclides
Waste/barrier/rock interactions: borosilicate glass release			
Waste/barrier/rock interactions: spent fuel release	<ul style="list-style-type: none"> Spent fuel matrix dissolution behavior: evaluate whether spent fuel undergoes stoichiometric or non-stoichiometric dissolution for key radionuclides 	<ul style="list-style-type: none"> Show stoichiometric dissolution of the spent fuel matrix, by showing that the ratio of radionuclides to uranium in the spent fuel matrix is the same as the ratio of respective radionuclides to uranium in the aqueous phase of spent fuel dissolution experiments 	7.5.3.5 Demonstrate stoichiometric dissolution limits for radionuclide release

PST87-2005-8.3.4-27

shown that spent fuel undergoes stoichiometric dissolution, the spent fuel testing program and radionuclide release modeling efforts may be significantly simplified. Technical Concern 7.5.3.6, entitled "Demonstrate Solubility Limits for Radionuclides," addresses radionuclide solubility behavior. If solubility limits can be established for key radionuclides, then radionuclide releases from the waste package can be conservatively modeled because these concentrations represent an upper concentration limit.

Information from other investigations or specific programs is an important aspect of the waste package radionuclide behavior investigation. The waste package environment program (8.3.4.2) establishes the expected repository conditions, and this information serves as the basis for the testing parameters used in the radionuclide behavior testing program. The waste forms investigation (8.3.4.3.3) provides the fundamental characterization of waste forms used in the testing program. If stoichiometric dissolution is determined to limit radionuclide release, information from the waste forms investigation concerning radionuclide inventories in the UO₂ matrix, cladding, and fuel-cladding gap will become even more critical for the experimental determination of expected radionuclide concentrations and the subsequent modeling of radionuclide releases from the waste package.

Several constraints will influence the ability to obtain repository-relevant experimental data. Such constraints are related to either experimental techniques or approach, or the ability to adequately characterize and simulate the waste package environment. Details of these constraints are given below.

1. Extrapolating short-term experimental data. Perhaps the most significant constraint facing the use of the experimental data obtained in support of the waste package radionuclide behavior investigation is the ability to confidently extrapolate short-term (i.e., 6- to 12-mo) experimental data to the 10,000-yr repository-relevant time frame defined by the regulatory criteria. Mass transport models for waste package systems indicate that radionuclide releases will be controlled by solubility-limited, transport control (NAS, 1983; Zavoshy et al., 1985; Apted et al., 1986). The present strategy is to obtain experimental data that will either bracket the actual solubility parameters in question, or clearly represent a conservative (in the sense that they represent maximum values) estimate of that parameter. For example, aqueous radionuclide concentration limits will serve to define conservative radionuclide release rates. This is based on the theory that the aqueous radionuclide concentration limits are controlled by the solubilities of secondary phases in the system. These secondary phases may be stable phases, but will more likely be metastable phases, given the short duration of the experiments. If the secondary phase is the most stable of possible phases, then the radionuclide concentration(s) will be controlled by this phase for constant repository conditions and can be conservatively used to evaluate long-term radionuclide release from the waste package.

However, if the secondary phase is metastable, radionuclide concentration(s) controlled by the solid phase will be time-dependent, and a step-wise series of intermediate, metastable phases, each more stable than the last, will form until a final stable phase forms (Ostwald Step Rule). The radionuclide concentrations controlled by these metastable phases will decrease with time until the concentration associated with the equilibrium phase is reached. Therefore, the initial aqueous concentration limit for a given radionuclide provides a conservative value for evaluation of radionuclide release from the waste package, regardless of the stability/metastability of the solubility-controlling solid phases. However, if the radionuclide of interest is not a major component of the solid phase but a trace constituent, the step-wise reduction of concentration with time is not valid. In such a case, an evaluation of the persistence of the initial, metastable phase formed under constant repository conditions is required to evaluate the applicability of the associated aqueous radionuclide concentration limit to long-term release analyses. If the metastable phase is determined to not persist with time, then the stable assemblage will be examined for its ability to serve as a host for radionuclides. Supporting information from the natural analogs and metallic artifacts investigation (8.3.4.2.4) will serve as the basis for such evaluations.

2. Simulating open-system conditions that would be present in a waste package located in basalt (i.e., extremely low groundwater flow rates, evolved groundwater compositions, fluid to rock ratios, and groundwater migration pathways).
3. Characterizing the presence and mobility of colloids.
4. Simulating the redox state of the waste package environment.
5. Accelerating reaction kinetics.
6. Determining the representativeness of the waste forms tested and the use of simulated waste forms. In the case of high-level waste, prospective producers have provided a reference waste form design composition that is used for the purpose of providing realistic laboratory simulations of these wastes. In the case of spent fuel; only a limited amount of such fuel is currently available for laboratory testing. The question of how representative the spent fuel and simulated high-level waste forms are of the actual waste form populations is addressed in Technical Concern 7.5.3.7 (see Section 7.5.3).
7. Determining analytical uncertainties (i.e., the magnitude of uncertainties of the measured solution concentrations of radionuclides).

8. Designing experiments to test the matrix dissolution behavior of spent fuel. Experiments will be constrained by the extremely low solubility of spent fuel and the analytical uncertainties of establishing a ratio not significantly different (as determined by statistical analysis) from 1.0 for the ratio of the radionuclide to UO_2 in spent fuel to the ratio of the radionuclide to UO_2 in test solutions.

Open-system and closed-system hydrothermal experiments will be used in a complementary manner to address most of the above constraints. An open system is a system that allows the transport of energy and matter across its boundaries. Experiments representing an open system are sometimes referred to as dynamic experiments. A closed system is a system that allows energy but not matter to be transferred across its boundaries. Experiments representing a closed system are sometimes referred to as static experiments.

Open-system experiments, which are designed to simulate porous medium flow, will (1) address the effect of waste package geometry on groundwater composition and radionuclides mobility, (2) better approximate the water to solid ratio expected in a repository, and (3) allow assessment of the mobility of colloids. Closed-system experiments are used to establish radionuclide concentrations that develop from the interaction of spent fuel and groundwater, with or without other waste package components. Open-system and closed-system experiments will effectively bracket the expected groundwater flow rate in the waste package environment.

Synthetic groundwater and altered waste package components will be tested in closed system experiments and compared with tests using unaltered material for the purpose of identifying any significant differences. Experiments will be prepared to induce a reducing environment, but the Eh of the system will be allowed to respond to conditions once the experiment begins. Tracer injection testing will be used to confirm the reduction of key radionuclides. Attempts to accelerate reaction kinetics will be made by crushing the components to be reacted and experimenting at high temperatures. Experiments will be conducted with components of different size fractions to assess the impact of varying surface areas on the experimental results. Confirmatory testing of waste forms representative of full-scale waste form production has been proposed to ensure that the simulated waste forms prepared for laboratory testing are indeed representative of the actual waste to be placed in a repository (see Section 7.5.3.7, Technical Concern 7.5.3.7). Various types of spent fuel will be tested to assess the variability of the release testing as a function of fuel type. Enhanced analytical techniques and replicate testing/analysis will be used to minimize analytical uncertainties.

8.3.4.3.6.3 Description of studies

An overview of the studies comprising the waste package radionuclide behavior investigation is presented below. The reader is referred to the following study plans for additional details:

1. Radionuclide Solubility/Sorption and Speciation Behavior Study Plan (Wood/IT Corp., 1987).

2. Waste/Barrier/Rock Interactions: Spent Fuel Release Testing Study Plan (Neal et al., 1987).
3. Waste/Barrier/Rock Interactions: Borosilicate Glass Release Testing Study Plan (Rawson and Neal, 1987).

8.3.4.3.6.3.1 Radionuclide solubility/sorption and speciation study.

The objective of this study is to quantify experimentally the mobility of important radionuclides in the waste package environment. Primary emphasis is placed on determining radionuclide behavior in the presence of basalt and packing material using the batch sorption technique. Four subordinate objectives of this study are to (1) develop experimental methods that simulate the waste package environment as accurately as possible; (2) interpret from the experimental data the reactions controlling the release of individual radionuclides; (3) accurately measure the solubility and sorption values; and (4) assess the reliability of the data interpretation. Data from this study will be used to evaluate the performance goals for the reduction of multivalent radionuclides and for determining radionuclide distribution coefficients and distribution equations. Table 8.3.4.3-11 presents the relevant test methodology and relevant parameters in summary form.

Environmental conditions that must be simulated over a range of appropriate values include temperature, groundwater composition, the redox state of the system, the nature of the sorbing medium and the water to rock ratio. An important yet difficult parameter to simulate is the appropriate redox. Much of the experimental design is focused on the best methods for demonstrating the rate capacity and final system state for redox reactions. The primary reactions that involve radionuclides are (1) dissolution/precipitation; (2) sorption; (3) desorption; and (4) formation of radio-colloids/pseudocolloids. Data being collected to determine which reactions dominate the behavior of specific radionuclides include the partitioning of radionuclides between solid and solution, identification of radionuclide-bearing precipitates or colloidal materials, and determination of radionuclide oxidation states in solutions and solids. Because of the importance of redox in the speciation and migration of multivalent radionuclides, additional experiments are being conducted in this study that specifically address the speciation behavior of key radionuclides in solution. These experiments will focus on the effects of radiation and inorganic and organic complexes on radionuclide speciation.

A supporting set of tests will be performed to evaluate the mobility of colloids in the packing. Parameters to be considered in these tests include temperature, water chemistry, packing material composition, density and size distribution, and type of colloid. Synthetic groundwater and potential or simulated colloids (e.g., silica and iron hydroxides) will be used in the experiments.

Table 8.3.4.3-11. Summary of tests in the radionuclide solubility/sorption and speciation behavior study

Test title	Abbreviated description of test method	Relevant parameters
Radionuclide solubility/ sorption and speciation behavior	Use batch sorption techniques to establish sorptive capacity of packing material and backfill (basalt). Evaluate redox conditions attained in experimental system. Establish maximum (bounding) concentrations of key radionuclides and generate sorption/ desorption isotherms. Determine the reactions that dominate the behavior of radionuclides, including the partitioning of radionuclides between solid and solution, the identification of radionuclide-bearing precipitates or colloids, and the oxidation state of radionuclides in solutions and solids. Determine the effects of radiation and inorganic and organic complexes on the speciation of key radionuclides.	Maximum (bounding) concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2) Redox conditions Kds for specific radionuclides

PST87-2005-28

92125550756

The reliability of the interpreted data will be assessed in terms of (1) the capability of the experimental method to approximate the waste package environment; (2) the identification of the correct chemical reaction involving the radionuclide in the experimental system; and (3) the accuracy and precision of the measurements. Statistical analysis of the data will be used. If the number of experimentally determined data points is insufficient to support use of statistical techniques, then the available data will be interpreted with expert judgment.

The data described above will be used to develop a conceptual model of radionuclide behavior and as input to performance assessment models that estimate radionuclide release rates from the waste package. The data form the basis for a conceptual model that defines which reactions control solution concentrations of specific radionuclides, the values of the solution concentrations, the variability of radionuclide solution concentrations relative to the range of expected geochemical conditions (especially the potential range of redox conditions), and the values of retardation factors (both sorption and desorption reactions included). These values are used in mass transport models that estimate radionuclide release from the engineered barriers system into the host rock. The base case model assumes maximum steady-state concentrations (i.e., solubility value) for most radionuclides and retardation coefficients. As more data are generated, the numerical values will be refined and other processes will be factored in as appropriate (e.g., adjustments to solubility values or retardation coefficients as affected by colloidal formation and transport).

Sorption and solubility data are derived from batch sorption type experiments that involve mixing doped synthetic groundwater solution with the reactive solid. The samples are placed in environmental shakers or autoclaves, depending on the experimental temperature (e.g., below and above 100 °C, respectively). An alternate experimental apparatus being developed is a recirculating column that has been designed to accelerate the reduction process. The parameters that are considered in test matrices include the specific radionuclide, the range of initial conditions, the sorbing medium, temperature, groundwater composition, redox state, water to rock ratio, the degree of packing alteration and the preexperimental sample treatment. Sample treatment enhances the reduction of the experimental system by removing as much oxygen from the system as possible prior to the experiment. This may be done by purging the groundwater with argon, crushing basalt under argon, or, in the case of an autoclave, purging the space above the solution with argon.

Data that are produced include initial versus final radionuclide solution concentrations over a range of initial concentrations, changes in solution concentration as a function of time, aqueous radionuclide concentration limits, speciation (oxidation state) of radionuclides in solution and reactive solid, and the identification of filtered radionuclide-bearing material (either precipitates or colloids). From these data, solubility values and sorption or desorption isotherms are generated. The duration of the tests is dependent on the time needed to reach steady-state conditions, which is, in turn, dependent on the behavior of the specific radionuclide and the temperature. The necessary number of experiments is dependent on expert judgment.

Colloidal transport experiments will be conducted only if it is determined that colloids are likely to form and be mobile in the packing material. Colloid transport experiments without radionuclides will be part of the packing material investigation (8.3.4.3.5). In colloid transport experiments involving radionuclides, the basic experimental setup will be a flowthrough column filled with crushed basalt or packing. A reservoir at the inlet end will be filled with groundwater that contains radionuclide-spiked colloids. The parameters to be considered include the specific radionuclide, the type of colloid (e.g., silica, bentonite, iron, iron oxide), the size of the colloid, the groundwater composition, and redox conditions. The data produced will include the radionuclide concentration in the effluent as a function of time and the radionuclide distribution in the column material. From these data, retardation coefficients can be calculated and compared with retardation coefficients determined from column experiments without colloids (see the physical properties and processes study (8.3.4.3.5.3.2) under the packing materials investigation). In this manner, the influence of colloidal transport on radionuclide mobility can be evaluated.

Alpha radiolysis experiments will be performed by placing radionuclide-bearing solutions in a radiation environment (i.e., a gamma radiation or alpha particle field). The parameters to be considered include the specific radionuclide, the initial radionuclide concentration, the dose rate, the total absorbed dose, the temperature, the reactive solid, the groundwater composition and the redox state. Using oxidation-specific extraction techniques or oxidation-specific spectroscopic techniques, the oxidation state of multivalent radionuclides and radionuclide concentrations will be measured as a function of time. The duration and number of tests are to be determined.

Inorganic and organic complexation experiments will be performed by adding various amounts of organic and inorganic complexants that might form stable complexants to radionuclide-bearing groundwater. The parameters to be considered include the kinds of inorganic and organic complexants that might be found in the waste package environment, the specific radionuclide, the initial radionuclide concentration, the temperature, the reactive solid, the groundwater composition, and the redox state. Analytical techniques such as oxidation-specific extraction methods, photoacoustic laser spectroscopy, laser-induced fluorescence spectroscopy, and liquid scintillation methods will be used to identify total radionuclide concentrations, complexation constants, and oxidation states. The duration and number of tests are to be determined.

In conjunction with the study of organic complexation of radionuclides, a series of analyses will be completed to identify the organic materials present in unaltered sodium bentonite. These results will be compared with those derived from organic analyses of sodium bentonite that has been exposed in laboratory experiments to alteration processes expected to occur during the lifetime of the waste package. These processes include dehydration, steam treatment and hydrothermal alteration. The total set of analyses will provide a sufficient basis to identify which organic substances are likely to survive in the waste package environment and may be potential sources of radionuclide complexation in solution or sorption on the solid substrate.

8.3.4.3.6.3.2 Waste/barrier/rock interactions:
spent fuel release testing study.

The objectives of this study are to (1) experimentally determine aqueous concentration limits of key radionuclides released from samples of actual spent fuel, (2) identify and characterize the secondary phases that are believed to control radionuclide concentrations, (3) evaluate the matrix dissolution behavior of spent fuel, and (4) evaluate the synergistic interactions within the waste package environment. Table 8.3.4.3-12 summarizes the relevant test methodologies and parameters relevant to spent fuel release testing.

The above objectives will be accomplished using hydrothermal experimental methods designed to test the behavior of spent fuel under simulated repository conditions. Data derived from these experiments will, in part, serve as the basis for evaluating whether the long-term radionuclide release criteria can be met. Specifically, determination of aqueous concentration limits (i.e., solubility limits) in these experiments will serve to define an upper (conservative) concentration boundary for key radionuclides in the saturated postclosure waste package environment. These concentrations will (1) be compared with concentrations generated by thermodynamic models such as EQ3/EQ6 (Wolery, 1981) to determine whether the concentrations are controlled by reversible equilibria and to help identify irreversible processes, and (2) serve as source terms for modeling radionuclide release from the waste package using codes such as CHAINT (Kline, et al., 1985). If stoichiometric dissolution of the spent fuel matrix can be shown to limit radionuclide release, the spent fuel testing program may be significantly simplified because only the behavior of the UO_2 matrix and a select group of radionuclides will require detailed investigation.

Three basic types of testing equipment are used in the spent fuel testing program for a variety of hydrothermal tests. Closed system (static) hydrothermal tests will be conducted in both Dickson-type pressure vessels and Parr-type vessels. Open system (dynamic) tests will be performed using specially designed flowthrough pressure vessels. The Dickson-type pressure vessels have an inner, compressible gold reaction bag with sufficient volume to load enough simulated groundwater with the solid components to allow periodic sampling of the fluid (at temperature and pressure) over the course (typically 6 to 12 mo) of the experiment. Also, Dickson-type vessels can be reinjected with fluids to maintain a specific liquid to solid ratio and to test the behavior of dopants.

Titanium Parr-type vessels are much smaller, can be sampled less frequently over the course of an experiment, and operate at the liquid/vapor pressure of water that corresponds to the particular temperature of the test. However, Parr-type vessels are very useful because they are less costly, easier to maintain, and can be used for long-term (i.e., 2- to 4-yr) experiments.

Table 8.3.4.3-12. Summary of tests in the waste/barrier/rock interactions: spent fuel release testing study

Test title	Abbreviated description of test method	Relevant parameters
Closed-system spent fuel testing	Hydrothermal interaction testing of spent fuel plus simulated groundwater with and without various waste package components at repository-relevant experimental conditions. Periodic at-temperature solution sampling over 6- to 12-mo durations for Dickson-type vessels and up to 4-yr durations for Parr-type vessels. Identification and characterization of post-quench solids.	<ul style="list-style-type: none"> Steady-state solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2)
Open-system spent fuel testing	<p>Two types of open-system testing will be conducted as follows:</p> <ol style="list-style-type: none"> (1) Flowthrough hydrothermal testing of spent fuel only in order to assess its dissolution behavior and dissolution rate at variable flow rates (2) Flowthrough hydrothermal testing of spent fuel with various waste package components in a manner geometrically consistent with the waste package. Periodic at-temperature solution sampling; variable flow rates. Removal of post-quench solids for characterization purposes. 	<ul style="list-style-type: none"> Maximum solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2) Release rate of uranium from spent fuel as a function of flow rate Ratio of radionuclides to uranium in solution
Closed-system tracer level injection testing	Hydrothermal interaction testing of spent fuel plus simulated groundwater with and without various waste package components at repository-relevant experimental conditions. Injection of tracer-doped groundwater after steady state has been reached. Periodic at-temperature sampling to monitor both the initial reaching of steady state and the return to steady state after injection. Allows steady-state concentrations to be established from both undersaturation and oversaturation. Promotes formation of secondary solubility-controlling secondary phases for characterization purposes.	<ul style="list-style-type: none"> Maximum solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2)

PST87-2005-29

The closed system (static) hydrothermal experiments, involving three or more waste package components, are incapable of simulating repository conditions to the extent that the progressive reactions between the groundwater, spent fuel, candidate container material, packing, and basalt host rock are maintained. However, the closed system experiments are a critical element of the spent fuel testing program because (1) they provide fundamental understanding of the bulk chemical reactions that are likely to occur in the waste package environment; (2) the radionuclide release rates can be conservatively modeled based on the aqueous radionuclide concentration limits achieved (i.e., the concentrations produced by these experiments are solubility-limited); and (3) these experiments are likely to best approximate the extremely low-flow conditions (i.e., they bracket the lower flow rate) of groundwater expected in the waste package.

In order to simulate the geometry of the waste package environment and to assess the impact of the waste package configuration on radionuclide concentrations, specially designed flowthrough pressure vessels will be used. The titanium reaction columns in these flowthrough pressure vessels can be packed with spent fuel and other waste package components in any desired combination, allowing the evolution of groundwater through the waste package to be characterized as it reacts in a step-wise manner with waste package components. Also, whereas the closed system experiments provide an absolute lower boundary for groundwater flow rate, the open-system experiments will provide an upper boundary. That is, the "no-flow" of the static experiments and the relatively high flow of the open system tests will effectively bracket the groundwater flow regime expected within the waste package environment.

The open-system, flowthrough tests will also serve as the basis of assessing the dissolution behavior of the spent fuel matrix. To establish that the spent fuel matrix dissolves stoichiometrically (see Technical Concern 7.5.3.5), it must be shown that the dissolving solids are released in their stoichiometric proportions. That is, the rate of release of a particular radionuclide is proportional to both the dissolution rate of the spent fuel and the relative abundance of the radionuclide in the spent fuel. To establish such a relationship experimentally, conditions must be such that the solubility limit for the radionuclides of interest is not reached. The reaction is forced to occur as a "surface reaction limited" reaction (see Apted et al., 1986); such a condition is readily feasible using an open-system experiment with a flow rate great enough to prevent solubility limits from being reached. Flowthrough columns will be packed with spent fuel only; replicate experiments and enhanced analytical techniques will be employed to reduce variability of the results. Due to the extremely low solubility of spent fuel, attempts will be made to accelerate matrix dissolution, if necessary. Both radionuclide concentrations and the UO_2 matrix dissolution rate will be the key parameters measured in these tests.

9 2 1 2 5 5 0 7 6 2

The confirmation that observed aqueous radionuclide concentration limits achieved in closed system tests are controlled by solubilities of secondary solid phases is performed by obtaining approximately the same aqueous radionuclide concentration limit from both undersaturated and oversaturated starting conditions. This will be accomplished by first establishing an aqueous concentration limit for a given radionuclide by reacting spent fuel + waste package components \pm groundwater in Dickson-type pressure vessels. Then, injection of small volumes of solution spiked with the radionuclide of interest in concentrations greater than the observed concentration limit will be performed. Upon injection, an increase in the radionuclide concentration above the initial aqueous concentration limit should result. If the concentration decreases to approximately the preinjection concentration limit over time, this (1) indicates that a solubility mechanism is controlling element (radionuclide) concentrations and (2) confirms that the radionuclide concentration represents the maximum concentration attainable for a given experiment. Repeated injections of radionuclide-spiked solution can be made to establish the reliability of this conclusion and, in addition, promote the growth of the solubility-controlling secondary phases to aid in identification and characterization efforts. If, after injection, the concentration does not decrease to roughly its previous concentration, this indicates that the particular nuclide of interest is inventory controlled.

For some radionuclides, it is possible that the bounding values obtained in static and dynamic experiments conducted using spent fuel and other waste package components cannot be established within the required degree of certainty. In such cases, simpler experiments will be conducted to measure the solubility of the relevant radionuclide-bearing solids. Nonradioactive or tracer-level hydrothermal experiments will be used to measure the solubility of well-characterized solids containing the element of interest. Information from these solubility tests will also aid in establishing solubility limits for radionuclides present in other waste forms (e.g., borosilicate glass) because these types of tests are not dependent on the waste form.

Test parameters to be measured include (1) the ratio of radionuclides to UO_2 for both the spent fuel matrix and the aqueous phase, (2) the aqueous concentration limits for radionuclides, and (3) the release rate of uranium from spent fuel. Test solutions from most of the experiments will be filtered in a manner that identifies the effects of colloidal-sized particles on radionuclide concentrations.

With the exception of radionuclide-specific solubility experiments and nonradioactive baseline experiments, all hydrothermal experiments will generally be conducted using two basic components (spent fuel and simulated Hanford groundwater) with and without various combinations of unaltered and altered host rock (basalt), unaltered and altered packing material (basalt-bentonite mix), Zircaloy cladding, candidate container materials (low-carbon steel, copper, or cupronickel--see Section 8.3.4.3.4), and filler materials. However, most testing will emphasize the spent fuel + water and spent fuel + container material systems. Also, some tests may be designed to specifically test the radionuclide releases from the Zircaloy cladding (i.e.,

test Zircaloy as the waste form instead of spent fuel). Nonradioactive developmental and baseline testing will aid in assessing possible radiolytic effects in the fully radioactive hydrothermal tests.

Temperatures of the experiments will range from approximately 90 to 200 °C. This temperature range is consistent with the anticipated temperature range in the repository (Yung et al., 1987). Experimental pressures will range from vapor pressure to 25 MPa (3,626 lbf/in²). Water to solid ratios in the closed system experiments will typically range from 10:1 to 60:1. The necessary number of experiments will be refined as experimental results are obtained and applied to performance assessment models. Test durations depend on the time necessary to achieve radionuclide concentration limits. Specific parameters measured in these experiments include pH, solution concentrations of major cations and anions, solution concentrations of radionuclides, evolved gas concentrations, and identification of secondary phases formed.

The commercial spent fuel tested to date is a nominal burn-up pressurized water reactor spent fuel. Testing of boiling water reactor spent fuel and other types of pressurized water reactor spent fuel will be undertaken in future tests to evaluate the range of variability in spent fuel release tests. Detailed characterization of the spent fuel(s) tested is a fundamental prerequisite of the spent fuel release testing program and such information is provided by the waste forms investigation (Section 8.3.4.3.3).

8.3.4.3.6.3.3 Waste/barrier/rock interactions: borosilicate glass release testing study.

The objectives of this study are to (1) experimentally determine aqueous concentration limits of key radionuclides released from fully radioactive borosilicate glass, (2) identify and characterize the secondary phases that are believed to control radionuclide concentrations, and (3) evaluate the synergistic interactions within the waste package environment. Table 8.3.4.3-13 summarizes the test methodologies and relevant parameters to be studied by the borosilicate glass release testing.

The above objectives will be accomplished using hydrothermal experimental methods designed to test the behavior of both defense and commercial borosilicate glass under simulated repository conditions. Data derived from these experiments will, in part, serve as the basis for evaluating whether the long-term radionuclide release criteria can be met. Specifically, determination of aqueous concentration limits (i.e., solubility limits) in these experiments will serve to define an upper (conservative) concentration boundary for key radionuclides in the saturated, postclosure waste package environment. These concentrations will (1) be compared with concentrations generated by thermodynamic models such as EQ3/EQ6 (Wolery, 1981) to determine whether the concentrations are controlled by reversible equilibrium and to help identify irreversible processes, and (2) serve as source terms for modeling radionuclide release from the waste package using codes such as CHAINT (Kline et al., 1985).

Table 8.3.4.3-13. Summary of tests in the waste/barrier/rock interactions: borosilicate glass release testing study

Test title	Abbreviated description of test method	Relevant parameters
Closed-system borosilicate glass testing	Hydrothermal interaction testing of borosilicate glass plus simulated groundwater with and without various waste package components at repository-relevant experimental conditions. Periodic at-temperature solution sampling over 6- to 12-mo durations for Dickson-type vessels and up to 4-yr durations for Parr-type vessels. Identification and characterization of post-quench solids.	<ul style="list-style-type: none"> Maximum solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2)
Open-system borosilicate glass testing	Flowthrough hydrothermal testing of borosilicate glass with various waste package components in a manner geometrically consistent with the waste package. Periodic at-temperature solution sampling; variable flow rates. Removal of post-quench solids for characterization purposes.	<ul style="list-style-type: none"> Maximum solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2) Bounding concentrations for uranium in solution
Closed-system tracer level injection testing	Hydrothermal interaction testing of borosilicate glass plus simulated groundwater with and without various waste package components at repository-relevant experimental conditions. Injection of tracer-doped groundwater after steady state has been reached. Periodic at-temperature sampling to monitor both the initial reaching of steady state and the return to steady state after injection. Allows steady-state concentrations to be established from both undersaturation and oversaturation. Promotes formation of secondary solubility-controlling secondary phases for characterization purposes.	<ul style="list-style-type: none"> Maximum solution concentrations for a specific suite of key radionuclides (see Table 8.2.2.1.5-2)

PST87-2005-30

Three basic types of equipment are used in the borosilicate glass testing program for a variety of hydrothermal tests. Closed system (static) hydrothermal tests will be conducted in both Dickson-type pressure vessels and Parr-type vessels. Open system (dynamic) tests will be performed using specially designed flowthrough pressure vessels. The Dickson-type pressure vessels have an inner, compressible gold reaction bag with sufficient volume to load enough simulated groundwater with the solid components to allow periodic sampling of the fluid (at temperature and pressure) over the course (typically 6 or 12 mo) of the experiment. Also, Dickson-type vessels can be reinjected with fluids to maintain a specific liquid to solid ratio and to test the behavior of dopants.

Titanium Parr-type vessels are much smaller, can be sampled less frequently over the course of an experiment, and operate at the liquid/vapor pressure of water that corresponds to the particular temperature of the test. However, Parr-type vessels are very useful because they are less costly, easier to maintain, and can be used for long-term (i.e., 2- to 4-yr) experiments.

The closed system (static) hydrothermal experiments, involving three or more waste package components, are incapable of simulating repository conditions to the extent that the geometrically controlled progressive reactions between the groundwater, borosilicate glass, candidate container material, packing, and basalt host rock are maintained. However, the closed system experiments are a critical element of the borosilicate glass testing program because (1) they provide fundamental understanding of the bulk chemical reactions that are likely to occur in the waste package environment; (2) the radionuclide release rates can be conservatively modeled based on the aqueous radionuclide concentration limits achieved (i.e., these experiments are solubility-limited); and (3) these experiments likely best approximate the extremely low-flow conditions (i.e., they bracket the lower flow rate) of groundwater expected in the waste package.

To simulate the geometry of the waste package environment and to assess the impact of the waste package configuration on radionuclide concentrations, specially designed flowthrough pressure vessels will be used. The titanium reaction columns in these flowthrough pressure vessels can be packed with borosilicate glass and other waste package components in any desired combination, allowing the evolution of groundwater through the waste package to be characterized as it reacts in a step-wise manner with waste package components. Also, whereas the closed system experiments provide an absolute lower boundary for groundwater flow rate, the open-system experiments will provide an upper boundary. That is, the no flow of the static experiments and the relatively high flow of the open system tests will effectively bracket the diffusional flow regime expected within the waste package environment.

The confirmation that observed aqueous radionuclide concentration limits in closed system tests are controlled by solubility of secondary solid phases is achieved by obtaining approximately the same aqueous radionuclide

concentration limit from both undersaturated and oversaturated starting conditions for a particular element. To accomplish this, the borosilicate glass testing program will use reinjection tests (Section 8.3.4.3.6.3.2).

Test solutions from most of the borosilicate glass experiments will be filtered in a manner that identifies the effects of colloidal-sized particles on radionuclide concentrations. The test parameters to be measured are the concentration limits for radionuclides in solution.

With the exception of nonradioactive baseline experiments, all hydro-thermal experiments will generally be conducted using two basic components (borosilicate glass and simulated Hanford groundwater) with and without various combinations of unaltered and altered host rock (basalt), unaltered and altered packing (basalt-bentonite mix), Zircaloy cladding, candidate container materials (low-carbon steel, copper, or cupronickel--see Section 8.3.4.3.4), and filler materials. The range of temperatures and pressures of the experiments will be similar to those used in the spent fuel tests. Water to solid ratios in the closed system experiments will typically range from 10:1 to 60:1. The necessary number of experiments will be refined as experimental results are obtained and applied to performance assessment models. Test durations depend on the time necessary to achieve aqueous radionuclide concentration limits. Specific parameters measured in these experiments include pH, solution concentrations of major cations and anions, solution concentrations of radionuclides, evolved gas concentrations, and identification of secondary phases formed.

The fully-radioactive borosilicate glass testing program to date has focused on simulated Savannah River Plant laboratory defense glass. Commercial borosilicate glass (e.g., West Valley Demonstration Project) and other defense glass (e.g., Hanford Waste Vitrification Project glass) will be tested in the future. Detailed characterization of the borosilicate glasses to be tested is a fundamental prerequisite of the borosilicate glass release testing program and such information is provided by the waste forms investigation (8.3.4.3.3).

8.3.4.3.6.3.4 Waste/barrier/rock interactions: other waste forms testing study.

The study plan that will support this testing program will be generated once the other waste forms (e.g., transuranic wastes) requiring testing have been identified by the DOE. The testing program for these other waste forms probably will be similar to those described for the spent fuel and borosilicate glass testing programs.

8.3.4.3.6.4 Application of results

The primary product of the radionuclide behavior investigation is the range of radionuclide concentrations anticipated for the predicted range of environmental conditions in and near the waste package. These concentrations

are used directly in radionuclide transport codes to model radionuclide releases from the waste package and to provide a source term to site transport codes for modeling radionuclide releases to the accessible environment.

If it is demonstrated that the spent fuel matrix dissolves stoichiometrically (see Section 7.5.3.5, Technical Concern 7.5.3.5), then the dissolution rate of the UO_2 becomes the critical parameter for the geochemical modeling effort, although aqueous concentration limits for those radionuclides not controlled by congruent dissolution (i.e., those radionuclides concentrated in the cladding, gap, and grain boundaries) will still be required for waste package release modeling.

This investigation also provides identification of solid phases that may control radionuclide concentrations. This information is used in geochemical codes such as EQ3/EQ6 (Wolery, 1981) to determine the stability of the alteration phase formed and in comparisons with natural analog information to evaluate the persistence of metastable alteration phases. Results of these types of analyses provide the basis for long-term extrapolation of radionuclide release performance of the waste package.

Lastly, this investigation provides information on radionuclide retardation behavior in the presence of packing. This includes providing radionuclide sorption equations (distribution coefficients, isotherms) that can be used directly in codes for modeling radionuclide transport or in evaluating effective radionuclide diffusivities in the packing.

8.3.4.3.6.5 Schedule and milestones

The four studies comprising the waste package radionuclide behavior investigation will provide data in support of the license application. Figure 8.3.4.3-6 summarizes the schedules and milestones for the waste package radionuclide behavior investigation. As indicated in Figure 8.3.4.3-6, the radionuclide solubility/sorption and speciation study will report (1) the speciation/complexation behavior of radionuclides in the waste package environment, (2) radionuclide solubilities to aid in the establishment of source terms, (3) sorption correlations and distribution coefficients for license application design waste package components, and (4) the effect of colloids on radionuclide concentrations in the waste package environment. Radionuclide source terms will be reported in Neal et al. (1987) and Rawson and Neal (1987). In addition, Neal et al. (1987) will provide a major milestone report on the feasibility of relying on stoichiometric dissolution to limit radionuclide release from the saturated, postclosure waste package environment. The data reporting milestone for the other waste forms testing study will likely be the same as the two previous studies, but the timing is to be determined.

ACTIVITY	TIME
RADIONUCLIDE SOLUBILITY/SORPTION AND SPECIATION	▽ ¹
WASTE/BARRIER/ROCK: SPENT FUEL RELEASE TESTING	▽ ² ▽ ³
WASTE/BARRIER/ROCK: BOROSILICATE GLASS RELEASE TESTING	▽ ⁴
WASTE/BARRIER/ROCK: OTHER WASTE FORMS TESTING	TBD

PS&B 2014 8.3.4-7

- ▽¹ REPORT RADIONUCLIDE SPECIATION/COMPLEXATION BEHAVIOR, RADIONUCLIDE SOLUBILITIES, RADIONUCLIDE SORPTION CORRELATIONS/DISTRIBUTION COEFFICIENTS, AND THE EFFECT OF COLLOIDS ON RADIONUCLIDE SOURCE TERMS.
- ▽² FEASIBILITY REPORT ON SPENT FUEL MATRIX DISSOLUTION BEHAVIOR
- ▽³ REPORT RADIONUCLIDE SOURCE TERMS FOR PERFORMANCE AND RELIABILITY ANALYSES.
- ▽⁴ REPORT RADIONUCLIDE SOURCE TERMS FOR PERFORMANCE AND RELIABILITY ANALYSES.

TBD ■ TO BE DETERMINED

Figure 8.3.4.3-6. Waste package radionuclide behavior investigation.

8.3.4.4 Specific program for waste package design development

The waste package design development program is one of four specific programs supporting the waste package program that will address activities related to the advanced conceptual design and license application design phases. The program described in this section consists of planned design and design-related activities that culminate in a waste package design that will accompany the license application submitted to the NRC. The other specific waste package programs address the waste package environment (Section 8.3.4.2), waste package materials and interaction testing (Section 8.3.4.3), and waste package modeling (Section 8.3.4.5). Plans for performance assessment of the waste package are described in Section 8.3.5.

Figure 8.3.4.4-1 shows this program and its relationship to other programs required to achieve a complete waste package design disclosure.

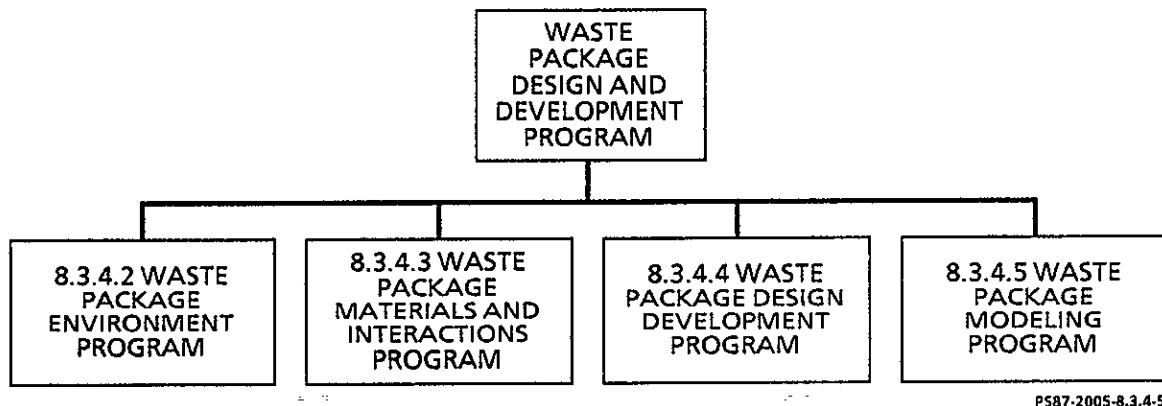


Figure 8.3.4.4-1. Waste package specific program relationships.

Background

Preliminary design, material, environmental, and analytical studies have been completed by the BWIP during the site characterization plan conceptual design phase to support the start of the advanced conceptual design. These activities were directed toward developing a preliminary waste package design for a repository in the basalt beds under the Hanford Site. They were accomplished in conjunction with similar studies on site configuration, site characterization, and repository design concepts for surface and subsurface facilities.

Conceptual design studies for the BWIP have been conducted over the past several years. Three major reports were issued. The first report (WHC, 1982) was completed in 1982 and was the first complete waste package and emplacement study for the program. The design emphasis was on placing containers in long, small-diameter boreholes that extended between two emplacement rooms. The second report (WHC, 1985), completed in 1984, emphasized the evaluation of

alternative waste packages and their interactions with several emplacement concepts. Twenty-three variations were included in this study. Based on these data and a corresponding study conducted by the BWIP architect-engineer, a third study (Gilbert/Commonwealth, 1987), was conducted and completed in 1986. This study report, called the Site Characterization Plan-Conceptual Design Report because it forms the technical basis for this SCP, placed emphasis on one specific design approach (steel container; preformed packing; short, horizontal borehole emplacement) and only two of the many waste forms (a particular pressurized water reactor spent fuel assembly and West Valley Demonstration Project high-level waste canisters). This SCP conceptual design report, while limited in its scope, did include a thorough engineering analysis of the resulting designs and showed that the approach selected would meet the design criteria (assuming follow-on tests would substantiate the assumptions used in the analysis). This SCP builds on that base, using the Gilbert/Commonwealth (1987) approach as the starting point for all design, material selections, and analysis.

Summary of program

This specific program comprises four major investigations: (1) design activities, (2) container development, (3) packing development, and (4) qualification testing. A description of each investigation is provided in the following sections. The first investigation addresses the basic design engineering and supporting analysis activities for the waste package. The second and third investigations are directed toward development of specific components of the waste package (container and packing). The last investigation addresses system level testing.

One component of the waste package system, the shell, has no development testing planned since it is a simple steel fabrication with no unusual features and has no postclosure performance function. The presence of the shell is included, however, in the related program activities of container-packing-shell interaction testing in the container materials investigation (Section 8.3.4.3.4).

The design activities investigation comprises four activity subsections whose detail planning will be provided in the waste package design development program. The activities are as follows:

1. Trade and engineering study activity--This section addresses engineering studies that are to be performed to support the start of advanced conceptual design.
2. Waste package configuration design activity--This section addresses the engineering design and analysis activities that will be performed to produce the advanced conceptual design and the license application design.

3. Container design and construction standard development activity--This section addresses the tasks that are performed to produce a standard that adapts the principles contained in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, to the particular needs of all repository projects: the BWIP (basalt); Deaf Smith, Texas (salt); Nevada (tuff); and crystalline rock.
4. Design-for-reliability activity--This section will address details of the design for reliability methodology program that comprises reliability allocation (probability and confidence level), design for reliability methodology development, and parameter experimental test design.

The container development investigation will address development of the waste package container and comprises the following four studies:

1. Pressure vessel container development study--This study will address the pressure vessel design concept, including the hot cell welding and nondestructive examination operations. This study includes work on single and bimetallic designs plus all container filler development.
2. Monolith container development study--This study will address the development program associated with the hot isostatic pressing process in which the waste form is fully surrounded by the sintered metal.
3. Container handling and safety study--This study will consist of a series of mechanical tests involving the assembled container and will include an accident event drop test.
4. Nonmetallic container development study--This study will address the feasibility (structural strength, fabricability, closure, etc.) of a nonmetallic container. This study will also include assessment of the feasibility of composite material containers and nonmetallic coatings on metallic structures.

The packing development investigation comprises the following three studies:

1. Packing fabrication study--This study addresses packing composition and preformed packing component fabrication. It will also address packing composition and fabrication/emplacement aspects for design options such as in-room emplacement where filled and tamped or pneumatically transferred packing emplacement will be considered.
2. Packing nondestructive examination study--This study addresses nondestructive examination for packing components during fabrication and prior to final assembly with the container or after emplacement.

3. Packing handling and emplacement study--This study addresses handling and emplacement equipment and process needs.

The qualification testing investigation will be directed toward studies that use large-scale (up to full-scale) components in an environment simulating the underground conditions during the repository postclosure period. The following studies are associated with this investigation.

1. Container corrosion test study--Corrosion rates associated with half- and full-scale models will be compared to corrosion rates determined by laboratory-scale (coupon sized) tests.
2. Packing saturation test study--The behavior of the packing during the saturation period will be determined.
3. Container settlement test study--The potential for viscoelastic response of the packing due to postclosure repository conditions and container-bearing loads will be determined.
4. Waste package in situ tests study--This study utilizes in situ emplacement testing for design confirmation in the repository during the construction and the operational phases. Aspects of the waste package design that affect the site, such as heat and stress due to waste package thermal output, are addressed in the section describing the exploratory shaft program.

In summary, these investigations (and subtier studies) are necessary to provide evidence that the waste package subsystem will satisfy the applicable regulatory requirements. This will be accomplished by planning the program in accordance with the licensing strategy, by obtaining the necessary information at the required data accuracy and confidence level, and by obtaining a peer review of the applicability and validity of each engineering task investigation (including subtier studies and analyses).

8.3.4.4.1 Purpose and objectives

The purpose of the waste package design development program is to produce (1) the BWIP waste package license application design and the supporting analyses and (2) a container design and construction standard for all sites. Prototype demonstration efforts will be performed to support the design and analytical activities for specific areas of the waste package design.

The waste package design development program includes the supporting engineering activities that contribute to the waste package subsystem design development. The activities include the following design related analyses, component development, and equipment development:

- Life cycle cost analysis.
- Waste package subsystem design-for-reliability methodology development.
- Waste package system design optimization model development.
- Waste package component development (this activity includes prototype and process demonstration activities).
- Waste package hot cell equipment development (accomplished in concert with related repository programs).
- Waste package handling equipment development (accomplished in concert with related repository programs).

Information provided by these activities will be used to determine whether the waste package will satisfy all applicable regulatory requirements.

8.3.4.4.2 Rationale

As previously stated, the advanced conceptual design and license application design and analysis activities build on prior work (WHC, 1982, 1985; Gilbert/Commonwealth, 1987). Prior work includes the design evaluations described earlier and the preparation of the strategy for resolving issues, Section 8.2.2. This SCP is based on the specific designs included in the SCP conceptual design report and the issue resolution process. Using these as a base, the BWIP developed design options that might be used to offset any weaknesses in the reference design. The four waste package specific programs (see Fig. 8.3.4.4-1) will provide data to evaluate the design options available to meeting the regulations. The reference and the options under consideration are presented in Table 8.3.4.4-1. The four waste package programs contain elements of work that address the options listed.

The work described herein will be performed during the next several years and will build on the work accomplished by the BWIP up to now. The major input to this work is the SCP conceptual design report (Gilbert/Commonwealth, 1987), which is the current reference concept. During the SCP conceptual design phase and the reviews that followed it, technical questions arose that must be addressed in the next stage of the program. To address some of the questions identified during the SCP conceptual design process and the technical concerns in Chapter 7, the BWIP has identified a number of waste package design options. These options (i.e., emplacement and package

Table 8.3.4.4-1. Reference and options being evaluated during site characterization

Reference design approach	Options under consideration
Emplacement system Short horizontal borehole (SHB) Decay heat limited to 2,200 W	<ul style="list-style-type: none"> • SHB with alternative packing arrangements (e.g., preforms plus pneumatic) • In-room emplacement • Alternate decay heat limits
Borehole Sized for nominal 15 cm (5.9 in.) of packing	<ul style="list-style-type: none"> • Size for alternate packing thickness
Container Steel, pressure vessel type Container lifetime beyond 1,000 yr Corrosion products not included in analysis	<ul style="list-style-type: none"> • Copper, pressure vessel type • Copper alloy, pressure vessel type • Bimetallic, pressure vessel type • Copper, monolith type • Steel, monolith type • Bimetallic, monolith type • Nonmetallic container • Long lifetime (e.g., beyond 10,000 yr) • Include in analysis
Filler Particulate	<ul style="list-style-type: none"> • Various particulates • Steel preforms • Low melting temperature castable metals
Packing Preformed packing segments Packing composition, 75:25	<ul style="list-style-type: none"> • Preforms plus pneumatic emplacement • Pneumatic plus tamped • Replace packing with backfill in emplacement room concepts • Different ratio for control over physical properties • Different ratio for control over chemistry • Steel shot (or other reductant) as additive
Shell No credit taken for shell	<ul style="list-style-type: none"> • Use corrosion products in analysis

PST87-2005-8.3.4-14

configurations and component materials) will be evaluated in a series of pre-advanced conceptual design studies to establish preferred concepts. These preferred concepts (about three but not more than six) will be selected as the basis to initiate the advanced conceptual design phase of the program.

There are three potential types of waste containers: pressure vessel (various metals), monolith (various metals), and nonmetallic (various ceramic and nonreactive materials).

In a similar fashion, the importance of the environment of the waste package, over its lifetime, will be addressed during the next several years of work. The program includes work on developing the knowledge of the environment (Section 8.3.4.2) and includes studies of the interactions of that environment on the various waste package components, as well as the impacts of the waste package components on each other (Section 8.3.4.3).

This entire waste package program (Section 8.3.4, coupled with activities regarding waste package-to-repository interfaces and overall system optimization) culminates in the selection of the waste package design. The waste package design engineering activity will include preparation of a complete Title II design disclosure (fabrication level drawings, specifications, mandatory procedures and processes, and the supporting design analysis). This final design work will include the component development and testing programs described in Section 8.3.4.4.

8.3.4.4.3 Design activities investigation

The design activities investigation comprises design- and engineering-related activities wherein the work does not involve testing and laboratory activities. The specifics of the activities will be detailed in the waste package design and development plan (as opposed to specifics of studies involving tests and laboratory work that will be detailed in individual study plans).

The design activities investigation is made up of four activities:

1. Trade and engineering study activity.
2. Waste package configuration design activity.
3. Container design and construction standard development activity.
4. Design-for-reliability activity.

8.3.4.4.3.1 Purpose and objectives

The trade and engineering studies comprise two main elements: (1) pre-advanced conceptual design studies and (2) advanced conceptual design supporting studies. The purpose of the trade and engineering studies is to enable the start of the advanced conceptual design program with a focused direction via activities that prescreen many of the options that are available to assist in meeting the regulatory requirements. Thus, the advanced conceptual design will be able to start with a limited number of options to be addressed. Likewise from this effort, there can be a modification of the supporting research and development programs to focus those programs toward the most promising candidate materials and design approaches.

The purpose of the design activity is to produce a complete engineering design for the waste package for presentation to the NRC in the license application submittal. The work is broken down into two major phases, advanced conceptual design and license application design, with five work divisions within each phase.

The BWIP has been assigned the task of preparing a DOE container design and construction standard for use by all repository projects. The output of this work will be a container design and construction standard that will be applicable to the license application design submittal for all sites. It is targeted to be approved for use in the license application design phase. The purposes of the activity are to have a common standard for all the projects to ensure consistency and quality and to gain acceptance with regulatory agencies, the technical community, and the public.

The BWIP waste package subsystem program will use a probabilistic approach design methodology to achieving a design solution, preparing test plans, and evaluating data. This work will be directed via the design-for-reliability methodology activity. This procedures is applied because a reliability goal is provided as a principal design requirement.

8.3.4.4.3.2 Rationale

This investigation is being conducted to develop the engineering data necessary to close the waste package issues. The relevant issues are as follows:

1. Issue 1.4 deals with substantially complete containment of radionuclides within the waste package subsystem. This issue covers the period from repository closure through 300 to 1,000 yr after repository closure.
2. Issue 1.5 deals with gradual release of radionuclides from the engineered barriers subsystem. This issue covers the period beyond that addressed by Issue 1.4 through 10,000 yr after repository closure.

3. Issue 1.10 addresses Waste Package postclosure design criteria of 10 CFR 60.135 (NRC, 1987a).
4. Issue 2.6 addresses preclosure design criteria of 10 CFR 60.135.
5. Issue 2.4 addresses retrievability of the waste package prior to closing the repository.
6. Issue 4.3 addresses aspects of waste package fabrication.
7. Issue 4.5 addresses waste package costs.

The overall plan for the development of the waste package system will be as follows:

- Characterize the waste package environment.
- Investigate potential waste package materials for applicability and licensability in the environment.
- Develop analytical techniques to evaluate the suitability of the design options.
- Investigate waste package subsystem and emplacement options that will meet regulatory requirements.
- Evaluate the performance, schedule, and life cycle costs associated with each design concept.
- Select a reference design and one or more backup designs for further evaluation during the advanced conceptual design phase.
- Select a reference design during the license application design phase for inclusion in the license application submittal.
- Obtain data necessary to close out all issues.
- Complete the license application design disclosure documentation: drawings, specifications, and design report (including all analyses).

The strategy and issues resolution section (Section 8.2.2) addresses the information needs that relate to the waste package. Table 8.3.4.4-2 also guides the reader to that data.

The design activity investigation will be coordinated and integrated with other waste package and repository programs. The methodology for this investigation follows the overall waste package program methodology shown in Figure 8.3.4.1-1.

Table 8.3.4.4-2. Issues related to the design activities investigation

Title	Abbreviated description	Synopsis of relevant strategy for technical concern	Relevant technical concern
Issue 1.1	Isolation system performance	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 1.4	Substantially complete containment	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 1.5	Gradual radionuclide release	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 1.10	Postclosure design criteria	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 2.4	Retrievability	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 2.6	Preclosure design criteria	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 4.3	Production technology	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2
Issue 4.5	Cost	Design waste package sub-system in accordance with strategy discussed in Section 8.2.2	See Section 8.2.2

PST87-2005-8.3.4-15

8.3.4.4.3.3 Description of activities

The following subsections provide a detailed description of each of the planned activity categories that make up this investigation.

8.3.4.4.3.3.1 Trade and engineering study activity.

The trade and engineering studies comprise a number of discrete activities designed to assist in the selection of waste package components and subsystem design features. The studies included in this activity encompass a design alternative evaluation typical of most design projects plus specific design evaluation tasks unique to the waste package program.

The activity is staged over the course of the program through the license application design submittal. There is a pre 30% advanced conceptual design phase, which is described herein. There are tasks, yet to be defined in detail, to successfully complete the design through the license application design phase.

While prior design studies have served the purpose of generally sizing the waste package and confirming technical feasibility of the approach, these earlier studies were not scoped to provide all the information described for the start of advanced conceptual design activities. These studies perform this function.

The initial work will be planned to support the start of the advanced conceptual design with a follow-on effort targeted toward the 30% design review reference design and backup design selections. Later efforts support the architect-engineer in areas where specific expertise is required to supplement the architect-engineer activities in the design and analysis tasks.

Data obtained from the trade studies will be incorporated into the architect-engineer advanced conceptual design engineering activity. The data obtained in these studies do not in themselves result in the closure of an information need; rather, the data will be used by the architect-engineer, coupled with other studies, to close out an information need.

A synopsis of the contents of each task is provided herein in Sections 8.3.4.4.3.3.1.1 through 8.3.4.4.3.3.1.7. The studies are presented in this order: (1) system and emplacement orientation and (2) component orientation working from the inside of the waste package outward--waste form, filler, container, packing, and shell.

The work summarized herein addresses that work currently identified to support the waste package advanced conceptual design. Details of the work will be included in the waste package design and development plan. (Study plans are not prepared for activities. Activities are defined in equivalent detail in the waste package design and development plan.) As additional special engineering expertise is deemed necessary to support the architect-engineer, the study requirements will be developed, the waste package design and development plan will be updated, and studies will be conducted.

8.3.4.4.3.3.1.1 Waste package system studies. Two individual studies are identified in this category.

Waste package system options

This study will build on the existing data base of system-level design studies and the design and performance issue resolution strategies to screen the multitude of waste package system options to a limited number. The output of this study forms the basis for establishing the scope of work in the advanced conceptual design screening phase.

The study will be similar to that of 1984 in which a contractor to the BWIP looked at 23 design and emplacement options, developed a numerical weighting system (using a Delphi approach), evaluated the options, and ranked them based on an evaluation of performance, cost, and schedule factors (Westinghouse, 1985). This study will use the same basic approach but will use updated strategy decisions, design data, and recent studies to refine the rankings. Initially, the list of design options may be substantial, such as 30 feature and emplacement options. The goal is to reduce the true candidates for the advanced conceptual design program to about six candidates (but the study will be flexible in this quantity to ensure that truly competitive design concepts will receive a full review in the architect-engineer screening phase).

Selected container geometries

This study will provide a strategy to accommodate, in a cost-effective manner, the wide range of thermal and dimensional variations associated with the many waste forms that will be emplaced in the repository. The study will result in a recommendation for a limited number of waste package container configurations that will serve the needs of all currently identified waste forms. The study will address the following.

- All identified waste forms.
- Minimizing the number of container designs and, in particular, minimizing the number of container diameters and wall thickness configurations.
- Standardization of components.
- Interfaces with all container processing and emplacement handling equipment.
- Potential spent fuel processing operations (short of full rod consolidation operations), such as removal of nozzles for length reduction.
- Rod consolidation operations.

- Combining rods and assemblies of various designs into a single container.
- The need for fillers to ensure a minimum packing smear density after container breach.
- The need for fillers to support the container wall and thereby provide longer container lifetime or permit thinner container walls.

The study will result in a recommendation on the number of waste package container variations that could serve all currently identified waste forms. This study will form the basis for the architect-engineer's activities in this area; the architect-engineer will refine this preliminary work during the advanced conceptual design period.

8.3.4.4.3.3.1.2 Emplacement studies. Two individual studies are identified in this category.

Emplacement and retrievability design features

The SCP conceptual design report (Gilbert/Commonwealth, 1987) scope of activities did not include a thorough investigation of the options for providing handling features on the waste package components. This study will build on this work and other related activities of the architect-engineer in this area. The initial work will be accomplished in time to support the architect-engineer in the 30% advanced conceptual design screening phase. Additional studies may be accomplished to support the architect-engineer's expertise in later phases of design.

Packing influence on design and emplacement

The SCP conceptual design report (Gilbert/Commonwealth, 1987) produced a design concept that would meet the waste package requirements (using the data and analysis techniques specified for the study). To achieve the necessary performance, the SCP conceptual design report engineers made some assumptions with respect to the emplacement borehole, shell, packing, and container geometries and tolerances. This study addresses these features and uses current data on mining and fabrication capabilities.

Specifically, the study will review the various fabrication aspects and suggest tolerances that are applicable to large numbers of large mass (weight) components. Likewise, the study will assess the state of the art with respect to borehole mining operations. These will be combined with the need to achieve an emplaced minimum "packing smear density," a property describing the effective packing density after it has expanded to fill all initial void space in the borehole. The effective smear density target is 1.7 g/cm^2 , a value determined in earlier laboratory studies, to yield acceptable chemical and hydraulic properties for the packing mixture. Design recommendations will be made for consideration by the waste package engineering staff in their advanced conceptual design design and life cycle costing activities.

8.3.4.4.3.3.1.3 Waste form studies. Three individual studies have been identified in this category.

Effect of uncertainties and variations in waste form receipt rate

This study provides an assessment of throughput, batch operations, and waste package decay heat effect on the repository operation, and, thereby, on the design of the waste package. Existing waste package studies have assumed an average spent fuel assembly delivered on a normal schedule. This study will assess any potential waste package design impacts and potential design improvements that could result from using the latest spent fuel decay heat and availability schedule.

Consolidation of Westinghouse 17x17LG assemblies

The Westinghouse 17x17LG assemblies are a small fraction of the total population but are significantly longer than other light water reactor assemblies. This study provides an evaluation of the potential to reduce the overall length of these special fuel assemblies so that the overall waste package length can be minimized and fewer container sizes are needed. The target maximum length is 450 cm (177 in.) the length of the next longest assembly.

A limited number of these assemblies will be emplaced--1,200 assemblies or 300 waste packages. These assemblies are uniquely long--505 cm (199 in.), and, as a result, will size the waste handling equipment and emplacement rooms. This study will determine if it is practical to reduce the length of these assemblies without full rod consolidation processes and thereby effect significant savings in project life cycle costs.

Rod consolidation geometry

This study is directed toward assessing the diametrical allowance necessary for consolidated rods. The SCP conceptual design report, when sizing the container inside diameter, allowed a very small clearance between the rods and did not consider the potential presence of any assembly hardware that might remain attached to a pin after disassembly. This study reviews all known spent fuel assemblies and assesses the clearances required for packaging the rods into a container.

8.3.4.4.3.3.1.4 Filler study. The SCP conceptual design report (Gilbert/Commonwealth, 1987) shows the presence of a filler inside the container to reduce the free volume inside of the container. The report assumed crushed basalt for the purpose of that study. This study will assess the feasibility of a variety of filler materials and shapes from both a waste package mechanical and chemical standpoint. The study will address the interactions between filler options and the remainder of the waste package system. The selected filler will be expected to perform one or more of the following functions:

- Reduce the free volume of the waste package and thereby aid in maintaining a minimum packing smear density.

- Provide structural support for the container wall.
- Assist in providing a reducing condition around the waste form.
- Reduce the internal free volume to aid in criticality control.

8.3.4.4.3.3.1.5 Container studies. Two individual studies have been identified in this category.

Impact of lithostatic pressure

This study provides an evaluation of the effect of a change in the design requirements to include in situ maximum rock stress loads (versus the current design basis hydrostatic load). The study does not include any assessment of the likelihood of such loads--just the impact to the waste package container design (and the related DOE container design and construction standard) if these loads must be reacted by the container. The study will include assessing the impact to all three basic container design approaches: pressure vessel (shell), monolith (solid), and nonmetallic (either shell or solid).

Effect of container fabrication finishes on economics and performance

This study addresses influences that the container external surface finishes are expected to have on corrosion rates, uncertainties in corrosion rate predictions, and the economics of life cycle costs. The study will include consideration of the surface finish both as fabricated and with degradation related to assembly operations and emplacement in the borehole. The study will recommend tentative "as-fabricated" finishes and a confirmatory corrosion test program as appropriate.

8.3.4.4.3.3.1.6 Packing studies. Two individual studies have been identified in this category.

Shield packing design concepts

The SCP conceptual design report (Gilbert/Commonwealth, 1987) design shows the use of packing as a means of shielding the emplacement room from the waste form radiation. The scope of the study did not allow investigation of design options for this element of the waste package from the handling, emplacement, and retrieval aspects. This study provides design suggestions to the architect-engineer for consideration in the advanced conceptual design phase.

Shield packing/closure plate tradeoff

A related study will assess the desirability of using a thick, metallic borehole closure plate in lieu of packing as a shielding element. There are potential handling, economic, and radiation shielding advantages to using a dense metal plug in lieu of the friable packing material. The results of the study will be used by the architect-engineer during advanced conceptual design.

8.3.4.4.3.3.1.7 Shell studies. There are no trade or engineering studies planned for the shell (as an individual component) to assist the 30% advanced conceptual design option screening task.

8.3.4.4.3.3.2 Waste package configuration design activity.

The waste package configuration design activity consists of the baseline engineering tasks for the waste package subsystem. The objective of this work is to produce a complete engineering disclosure package for the waste package subsystem using the information obtained in all supporting waste package activities. These design and analysis activities culminate in the license application design that will be submitted to the NRC. The work will be conducted by the architect-engineer with some support by other design and engineering organizations. The details of the design activities effort synopsized herein will be provided at a later date in the waste package design development plan.

The design study will be conducted in two basic phases: advanced conceptual design and license application design. Each phase will have five subdivisions: 30%; 60%; 90%; the draft report preparation period (termed issue for approval); and the final period of external review, comment negotiation and incorporation, and report publication (termed external review phase).

8.3.4.4.3.3.2.1 Interfacing programs. Throughout the advanced conceptual design and license application design phases, interface activities will occur between the integrating contractor and the architect-engineer. The interface includes all BWIP-related activities. The engineering activities described herein will be integrated into the baseline program in a controlled and timely manner to ensure a cost-effective and technically acceptable engineering program. These interfacing activities include a wide range of studies. Examples include supporting technical analyses performed by the integrating contractor, emplacement and retrieval studies provided by repository design activities, and container weld process development by the Salt Repository Project.

8.3.4.4.3.3.2.2 Advanced conceptual design, 30% phase. Prior to the start of the 30% advanced conceptual design phase, the trade and engineering studies described in the prior section will have provided a preliminary screening of the many possible design options to a manageable few--approximately six in number. The advanced conceptual design will commence with these design concepts as well as with all other data from the testing and analysis programs in the waste package program.

The objective of this phase is to further screen the design options down to two or three for further study during advanced conceptual design. These will be designated on the reference design and the backup design(s). None of these are necessarily identical to the present SCP conceptual design report design.

Since this activity is mainly one of assessing the relative merits, advantages, and disadvantages of the various concepts, the effort will concentrate on studies, with design and analysis activity limited to that necessary for adequate screening evaluations. Throughout the program, commencing in the 30% advanced conceptual design phase, the design staff will perform engineering studies as part of the design selection, development, and analysis tasks. A listing of the types of studies that will be performed during the program is given in Table 8.3.4.4-3.

The phase will culminate in a formal design review that will document all decisions made in the design screening process. The design review report will be published documenting the work done during that period and will be formatted in accordance with DOE guidance. A considerable portion of the report is expected to consist of appendixes dealing with specific areas of interest (such as design alternatives considered, standardization of designs for all waste form variations and similar special subjects).

8.3.4.4.3.3.2.3 Advanced conceptual design, 60% phase. The goal of the 60% advanced conceptual design activity will be to develop the design and supporting analyses for the reference and backup designs waste package configurations that were identified for further study. Open items from the 30% phase will be addressed. Planning for subsequent design activities and prototype test preparation will be refined. An in-progress design review will be used to document the design process for this phase.

8.3.4.4.3.3.2.4 Advanced conceptual design, 90% phase. The 90% advanced conceptual design phase will be an extension of the 60% phase. In-progress review results from the 60% review will be factored into design and engineering considerations at the start of this phase. Generated data will be applied to refine the waste package design for the advanced conceptual design report.

8.3.4.4.3.3.2.5 Advanced conceptual design, issue for approval phase. This phase of activity is directed toward responding to the comments of the 90% design review and completing the draft advanced conceptual design report. The draft advanced conceptual design report will contain the technical, cost, and programmatic justification for the selection of the advanced conceptual design report reference and backup designs. The report will also contain (or reference) any special studies that have been prepared in support of the advanced conceptual design selection process.

8.3.4.4.3.3.2.6 Advanced conceptual design, external review phase. This is the final phase of the advanced conceptual design. It is composed of the following elements:

- Reviews of the advanced conceptual design and supporting engineering activities by the DOE.
- Response to the review comments by the architect-engineer, the BWIP, and other contractors supporting the design activity.
- Release of the advanced conceptual design report.

Table 8.3.4.4-3. Summary of activities to be conducted by the architect-engineer during advanced conceptual design and license application design

Basis design engineering activity	Advanced conceptual design				License application design			
	30%	60%	90%	IFA	30%	60%	90%	IFA
Engineering and design trade-off studies	P	I	I	I	I			F
Design sensitivity study	P	I			F			F
Life cycle cost data acquisition and model preparation	P	I	F	F				F
Life cycle cost design optimization		P	I	I	F			F
Weight and balance		P	I	I	I	F	F	F
Hazards analysis		P	I	I	I	F		F
FMEA analysis		P	I	I	I	F		F
MORT analysis		P	I	I	I	F		F
RAM analysis		P	I	I	I	F		F
Structural analysis	P	P ^a	I	I	I ^b	F	F	F
Thermal analysis	P	P	I	I	I	F	F	F
Shielding analysis		P	I	I	I	F	F	F
Criticality analysis	P	I	F	F				F
Corrosion analysis	P	P	I	I	I	F	F	F
Container lifetime analysis	P	P	I	I	I	F	F	F

^aStructural design for advanced conceptual design to be based on draft 1 of proposed container design standard.

PST87-2005-8.3.4-6

^bStructural design for License application design to be based on rev. 2 of proposed design standard.

NOTE: F = Final work, ready for publication and review as LA submittal.
 I = Intermediate level as necessary for selection and screening.
 IFA = Issue for approval.
 P = Preliminary, scoping activity.

Concurrent with external review activity, the architect-engineer will continue normal engineering activities in preparation for the license application design startup. They will respond to the review process critiques as they are presented so as to minimize the difficult final editing and publication process.

8.3.4.4.3.3.2.7 Interprogram phase. The period between the end of advanced conceptual design and the start of license application design provides time for all necessary license application design startup activities. These activities include updating of data bases, refinement of computer codes to be used in license application design, completion and approval of design requirements for the license application design phase, and similar activities. This time will also be used to conduct special studies that are applicable to the critical 30% license application design selection process. These studies will be identified as a result of the advanced conceptual design review and comment period critiques.

8.3.4.4.3.3.2.8 License application design, 30% phase. In the initial phase of license application design, any unresolved comments from the advanced conceptual design phase will be addressed and the design selection process will be conducted in sufficient depth to support a single reference concept selection. (Delaying the selection of the reference design until this point in the program maximizes the quantity of technical data available for selection of the reference concept.) Data will be keyed to feed into the decision at the latest practical time. The data will come from sources such as the container design and construction standard development activity, container development investigation, packing development investigation, container materials testing investigation, analysis activities, repository activities, and environment characterization studies. The design review for this phase will document the rationale and justification for the selection of the reference concept.

8.3.4.4.3.3.2.9 License application design, 60% phase. This phase concentrates on the preparation of drawings, specifications, and supporting analysis for the waste package components using the design selected in the prior phase (including any critique of that selection resulting from the design review). Because the waste package will be on the "Q-List" of critical components, the drawings and specifications will be complete (ready for fabrication), a state normally termed Title II. The engineering activities will include extensive analytical work as appropriate to support the design and to satisfy the BWIP information needs.

A design review will be held for comments on the work completed and to obtain feedback on areas that need reinforcement prior to completion of the license application design submittal.

8.3.4.4.3.3.2.10 License application design, 90% phase. This is the final design engineering phase of the program. The deliverable will be a license application design and supporting engineering documentation that will address every issue and information need and show how the waste package data are used to close out all issues. The final activity in this phase is a design review during which the design and supporting document will be examined for completeness and the ability to close out all issues.

8.3.4.4.3.3.2.11 License application design, issue for approval phase.

This phase of the license application design activity is directed toward responding to any residual concerns from the 90% design review and completing the draft license application design report. The draft license application design report will contain the technical, cost, and programmatic justification for the selection of the license application design. The report will also contain (or reference) any other special studies that are pertinent to the waste package issues and the ability of the BWIP design to meet all requirements.

8.3.4.4.3.3.2.12 License application design, external review phase.

This is the final phase of the license application design program. It comprises three main elements:

- Review of the draft license application design report by the DOE.
- Response to any comments by the combined technical staffs of the architect-engineer, the BWIP, and any consulting engineering firms.
- Final publication of the license application design report after all comments and critiques have been resolved to the satisfaction of the DOE.

8.3.4.4.3.3.3 Container design and construction standard development activity.

The purpose of this activity is to produce a waste package container design and construction standard that, when applied, will ensure that the desired container structural strength and quality will be attained. Activities associated with the container standard development will include:

- Failure mode identification and analysis.
- Design and construction rule development.
- Theoretical basis document preparation.
- Application manual preparation.
- Material property tests.
- Structural strength tests.

The standard will be applicable to the BWIP, salt, tuff, and crystalline rock projects. It will encompass all viable materials of construction and configurations being considered for the waste package container by the repository projects. The BWIP integrating contractor will ensure that the standard addresses the interests of each repository project. The standard will be approved and issued by the DOE to the integrating contractor at each project and subsequently provided to each project architect-engineer by the associated integrating contractor. It will be applied by each project architect-engineer to support waste package container design.

Information provided by the standard will be directly applied to achieve the container performance and reliability goals established by the performance assessment activity.

The design and construction standard to be produced by this activity will consist of three documents: a standard rules document, a theoretical basis document, and an application manual. The standard rules will comprise structural strength and fabrication related rules that will be applied to ensure relevant regulatory requirements are satisfied. The theoretical basis document will contain the theoretical justification for failure mode selection and strength-related rules. The application manual will contain application instructions.

The standard rules will contain material, design, fabrication, examination, testing, and documentation related rules. These rules will ensure that approved construction materials, fabrication and examination procedures, and design methods are applied. They will also ensure that appropriate documentation is provided and that the desired container quality requirements are specified.

The theoretical basis document will contain a justification for each credible failure mode and a theoretical basis for the associated design rules. This information will provide justification for rules contained in the construction standard. It will provide justification for design activities that establish container parameters and for construction activities that establish container quality. The theoretical basis document for the construction standard will provide the theoretical basis and the design rules for waste package containers, just as the Criteria Document for the American Society of Mechanical Engineers Code, Section III, and Section III of the Code itself provide the theoretical basis and design rules for pressure vessels.

An applications manual will be developed and provided in conjunction with the standard to illustrate application of the structural criteria. The manual will provide an explanation of the criteria and an interpretation of the inherent design margins associated with a probabilistic design methodology.

Reliability goals will be integrated into the construction standard development activity, to provide a mechanism by which to assess how well regulatory requirements pertaining to containment and radionuclide release rate are satisfied.

The standard will be based on probabilistic methodology assuming that initial studies on the probabilistic methodology confirm its applicability. Design rules and fabrication-related nondestructive examination currently have a deterministic basis. To ensure protection against potential failure modes in accordance with the deterministic methodology, safety factors will be applied to either the calculated stress-related quantities or to the measured material-related parameters. Design-for-reliability techniques will be applied to assess the container reliability and insure the container reliability meets the allocated reliability goal.

Development activities associated with a deterministic based standard began in fiscal year 1984. Subsequent program decisions concerning the deterministic versus probabilistic design approach have selected the probabilistic approach. The completed standard, using a probabilistic basis,

will be available to be released by the DOE for application by the repositories at the beginning of Title II license application design phase, 60% license application design.

Activities that were completed in fiscal year 1987 consist of the following:

- Alternate short-term criteria identification.
- Waste package container structural design philosophy report based on a deterministic methodology.
- Design rule definitions for the deterministic methodology.
- Example application of the deterministic design rules (i.e., example design report preparation).
- Applicability of existing codes and standards (short-term failure modes).
- Deterministic based standard rules (material, fabrication, inspection, testing, and documentation).

Activities that are planned for completion by the end of advanced conceptual design comprise the following:

- Convert the application basis for the standard (i.e., deterministic vs. probabilistic).
- Identify deformation-related, long-term failure modes and provide a basis to design for protection against the relevant failure modes. Apply deformation mechanism methods to identify the long-term failure modes.
- Prepare a theoretical basis document for the standard that provides a justification for each failure mode (short-term, long-term, and environmentally related) and a theoretical basis for the associated design rules.
- Prepare an applications manual.
- Obtain peer reviews.
- Prepare refined drafts of the standard.
- Prepare a design standard confirmation test program.
- Complete review and approval of the draft standard by the DOE.

Activities that are planned after completion of advanced conceptual design and prior to 60% license application design comprise the following:

- Prepare a completed design and construction standard.
- Obtain the DOE review and acceptance of the standard.
- Release the standard for application.

The studies associated with this activity will be performed by study contractors and the results will be integrated into the planned documents. Document approval will be obtained from the DOE, and the approved document will be provided to the architect-engineers by the integrating contractors.

8.3.4.4.3.3.4 Design-for-reliability activity.

Design-for-reliability methodology will be applied to the waste package design effort to ensure that the subsystem will meet assigned performance goals. These goals will be established to comply with the BWIP performance allocations on subsystem (and component level) functional performance. A detailed description of activities related to development and application of the design-for-reliability methodology will be provided in the design development plan.

This program task provides the design tools necessary to design the waste package subsystem, to the component level, with performance reliabilities that meet or exceed the performance requirements. Via this methodology, the experiments will be scoped, data acquired at the necessary level of precision, probabilistic density functions obtained on the design parameters, and reliabilities calculated using probabilistic techniques. As may prove necessary, the designs may be modified for improved reliability or alternate performance goals established (wherein areas demonstrating higher than required performance can assume a greater portion of the overall waste package subsystem requirements). This program is complemented by the reliability assessment program (8.3.4.5), which performs an independent assessment of the final design of the waste package subsystem working in concert with all other safety systems.

A reliability goal (the conditional probability and the associated confidence level) will be allocated to the waste package subsystem (and its components) for each regulatory requirement. The reliability goal for a particular regulatory requirement will be the desired probability and confidence level that the waste package subsystem (and its components) will satisfy the performance goal assigned to the requirement. Reliability models will be applied to allocate reliability goals to tests in the supporting studies. Reliability engineering techniques will be applied to design each test for a particular parameter to achieve the allocated reliability goal.

8.3.4.4.3.4 Application of results

The investigation will provide a complete design disclosure package for use in the license application design phase. Relevant information will be applied to support repository design, guide material characterization

activities, guide development testing, guide qualification testing, and provide the data base for safety, performance, and reliability analyses. The information will be applied to satisfy and close out technical issues developed by the DOE and the BWIP (see Section 8.2.2).

Information provided by the trade studies activity will be applied to support the initial option-screening effort. The waste package configuration design activities will provide the baseline engineering that culminates in a license application design. Container design and construction-related criteria will be provided by the container design and construction standard development activity. Design-for-reliability methods will be provided in that activity. These studies will be integrated to provide a waste package design that will satisfy regulatory requirements and close the related waste package issues (e.g., Issues 1.4, 1.5, 1.10, and 2.6).

8.3.4.4.3.5 Schedule and milestones

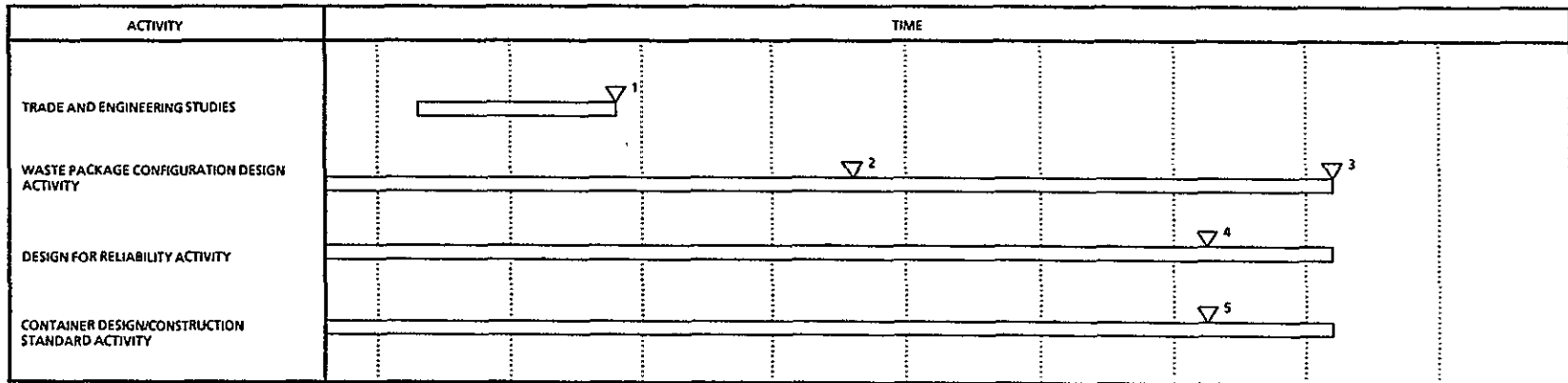
Figure 8.3.4.4-2 provides an overview of the schedules and important milestones for the design activities investigation.

8.3.4.4.4 Container development investigation

Within the waste package design development program, the container development investigation will satisfy information needs by providing the following study plans: (1) pressure vessel container development, (2) monolith container development, (3) container handling and safety testing, and (4) nonmetallic container development. The information produced by these studies will be supplied to the waste package materials and interaction testing (Section 8.3.4.3), waste package design development (Section 8.3.4.4), and the waste package modeling (Section 8.3.4.5) programs. The investigation also provides information to the design optimization program (Section 8.3.2.4), which is within the repository program.

The schedules of the container studies are structured to supply information to the waste package design development program at times relevant to the design screening and selection schedule as well as the completion of the license application design. The scope of the studies covers all aspects of components fabrication with the resulting data to be used in the license application design. The container handling and safety testing study will initiate testing at the conclusion of the advanced conceptual design. Accordingly, the test program is defined only to the general planning level.

The studies support the identified technical concerns from several issues, principally Issues 1.4, 1.5, 4.3, and 4.5, as well as the related issues using the waste package container as a component (Issues 1.1, 1.10, 2.4, and 2.6).



PS&S 2014-8.3.4.4

- ▽ 1 COMPLETE PRE-ACD STUDIES.
- ▽ 2 COMPLETE ACD DESIGN ACTIVITY; ISSUE ACD REPORT FOR APPROVAL
- ▽ 3 ISSUE APPROVED LAD REPORT.
- ▽ 4 PROVIDE INDEPENDENT RELIABILITY REPORT FOR LAD.
- ▽ 5 PROVIDE INDEPENDENT LAD REPORT.

ACD = ADVANCED CONCEPTUAL DESIGN
LAD = LICENSE APPLICATION DESIGN

Figure 8.3.4.4-2. Design activities investigation.

8.3.4.4.4.1 Purpose and objective

The purpose of the container development investigation is to accomplish the following objectives:

- Develop and qualify manufacturing and quality control processes.
- Provide technical information on the as-fabricated mechanical properties of the container materials.
- Produce test coupons for corrosion studies.
- Provide technical data for the container design.
- Produce specifications for container fabrication that will be included in the waste package container design.
- Produce prototypes that will be used for test purposes in other studies.
- Design and construct a prototypic hot cell simulator for manufacture of prototypes and other related process development.
- Assist in the development of the in-cell process and handling equipment via the prototypic facility operations.
- Provide data to support the license application design submittal, including closing out of all technical concerns and issues.
- Qualify the container for safety and handling by testing.
- Provide sufficient diversity in the design options being developed to permit variations in waste package subsystem design options and reliability reallocations, yet maintain the license application design submittal schedule.

8.3.4.4.4.2 Rationale

Three studies are directed toward the development of different basic concepts of containers: the hollow metallic pressure vessel concept (e.g., the Gilbert/Commonwealth (1987) concept), a solid metallic container that fully encapsulates the waste (the monolith concept), and the nonmetallic container concept of either hollow or solid configurations. The nonmetallic container concept may encompass material combinations such as coating and composites and may in fact include metallic components. The fourth study provides confirmatory data on the suitability of the selected container design to meet safety and handling requirements.

The two metallic container studies are complete in that each assumes that the subject study concept will be the one selected for the license application design. The full plan for development of the container is included in the studies. When the design screening and selection process results in screening out a concept, that program will then be terminated. The nonmetallic container program is known to have considerably more developmental risk and has only been planned to the license application design selection point. In this particular study, if the nonmetallic design approach is selected, the remainder of the study will be developed and interfaced with the other waste packaged design development activities (although slips in the overall schedule can be expected if this concept is selected).

The pressure vessel study incorporates the DOE plans for having the Salt Repository Project perform much of the basic steel weld and closure development activities. Via this cooperative effort, redundancy in the development programs will be eliminated to the maximum extent practical (when considering the design differences between the two sites).

The SCP conceptual design waste package container design includes the use of a filler inside the container. Other concepts and variations may also use a filler. The pressure vessel container development study will consider various fillers and will direct filler development activities for all container concepts.

The two metallic container studies are arranged into a three-phase approach. The three phases of each metallic container development study are similar: Phase 1 concentrates on initial laboratory-scale development activities; Phase 2 produces engineering scale (e.g., half scale) containers; Phase 3 produces full-scale prototypes. To accomplish the full-scale demonstrations, prototypic facilities will be established to be used in the final development and demonstration activities. These facilities will be fully equipped hot cell simulators.

The nonmetallic container study has four general phases of identified work: (1) candidate material selection, (2) manufacturability assessment, (3) design and reliability assessment, and (4) preparation of a follow-on plan (for use if the nonmetallic container approach is selected).

The container handling and safety testing study will begin during 60% license application design. The timing of the tasks within each phase is planned to support the design decision point timing outline in the issues section (Section 8.2.2). The constraints imposed on this investigation are minimal. They include the following:

- The program must provide data that match the design decision dates of the master program schedule.
- The loaded container weight will be restricted to a value (to be determined) that is compatible with the repository handling and hoisting capabilities. (The limiting facility may be the shaft hoists.)

The technical concerns are listed in Section 7.5. The technical concerns and corrective options relevant to this investigation are listed and correlated to the three container study plans in Table 8.3.4.4-4.

8.3.4.4.4.3 Description of studies

The studies will use a probabilistic design approach and will be structured to provide the necessary data to demonstrate the allocated component reliability levels. Since the allocations of performance to the container will vary as the program progresses, the study tasks will be designed to provide the maximum flexibility in accommodating the evolving reliability requirements.

The tasks to be accomplished during these studies include the development of container component fabrication methods and techniques, container assembly methods, container quality control methods (nondestructive examination), and the critical closure configuration.

8.3.4.4.4.3.1 Pressure vessel container development study.

The objectives of the pressure vessel container development study are as follows:

- Provide information relative to the waste package system and subsystem design effort.
- Determine the most suitable container filler material, form, and the method of installation.
- Determine the ease of fabrication of candidate container materials.
- Select the most applicable bimetallic material combinations and fabrication methods.
- Develop the most cost effective and reliable container component fabrication methods.
- Develop the container closure method.
- Identify the quality control examination methods to be used.
- Produce prototypes to be used for testing.
- Design and construct a prototypic hot cell fabrication facility.
- Provide information which will assist in the resolution of the technical concerns identified in Section 7.5.3.

Table 8.3.4.4-4. Relevant technical concerns and corrective options versus study plan (sheet 1 of 3)

Technical concerns (Section 7.5.1.2)	Option	Study plans		
		Pressure vessel	Monolith	Nonmetallic
1. Determining redox reaction rates and reduction capacity of materials in the repository environment	Add reductant (e.g., iron/steel shot) to the packing, inside the container, or in the backfill, or use a steel container to promote anoxic conditions	X	X	
	Use a different container material (e.g., a long-lived, nonmetallic material that is insensitive to Redox conditions)		X	X
2. Establishing the mechanical loading condition on the waste package	Use a different container configuration. Design the waste package to accommodate rock loading	X	X	X
3. Establishing groundwater flow rates in the repository after saturation	Place more reliance on the container	X	X	X
4. Determining time of packing resaturation	Use a different container material (e.g., on that is less sensitive to corrosion in a steam environment)	X	X	X
5. Demonstrating stoichiometric dissolution limits for radionuclide release	Utilize a long-lifetime container (e.g., 10,000 yr)	X	X	X
6. Demonstrating solubility for radionuclide solution limits	Add a reductant (e.g., iron/steel shot) to the packing, inside the container, or in the backfill, or use a steel container to promote anoxic conditions	X		
	Take credit for steel corrosion products (if appropriate) to reduce solubilities	X	X	
	Use long-life container (e.g., 10,000 yr)	X	X	X
8. Predicting of long-term container corrosion performance using short-term data	Uniform corrosion technical approach			
	Adopt an alternate design (e.g., bimetallic) using materials with known corrosion behavior to enhance corrosion resistance.	X	X	X
	Select a more corrosion resistant material (e.g., metallic or nonmetallic)	X	X	X
	Pitting corrosion technical approach			
	Use a different container material that exhibits more resistance to pitting corrosion (e.g., another metal, a bimetallic combination, or a nonmetallic in that order of consideration)	X	X	

PST87-2005-8.3.4-56

Table 8.3.4.4-4. Relevant technical concerns and corrective options versus study plan (sheet 2 of 3)

Technical concerns (Section 7.5.1.2)	Option	Study plans		
		Pressure vessel	Monolith	Nonmetallic
8. Predicting long-term container corrosion performance using short-term data (cont.)	If necessary, design a pitting corrosion allowance into the container wall thickness	X	X	
	Environmentally assisted cracking (EAC) technical approach			
	Use a different container material. The material would be changed to a more EAC-resistant material (e.g., another metal, a bimetallic, a nonmetallic in that order of consideration)	X	X	X
	Use a different container configuration. This would be employment of a nondeforming filler material to ensure that the container does not encounter strain rates of a high enough magnitude to cause EAC, or some other means of reducing the stresses and strains in the container wall	X	X	X
	Crevice corrosion technical approach			
	Use a different container configuration to preclude "vulnerable crevices" (e.g., crevices not protected by galvanic effects)	X	X	X
	Use a different container material that exhibits more resistance to crevice corrosion (e.g., another metal, a bimetallic combination, or a nonmetallic in that order of consideration)	X	X	X
9. Demonstrating microbial effects on corrosion	If necessary, design a crevice corrosion allowance into the container wall thickness	X	X	
	Use a different container configuration. The container design could be changed to a more conservative configuration such as a thicker wall with greater corrosion allowance	X	X	X

PST87-2005-8.3.4-56

Table 8.3.4.4-4. Relevant technical concerns and corrective options versus study plan (sheet 3 of 3)

Technical concerns (Section 7.5.1.2)	Option	Study plans		
		Pressure vessel	Monolith	Nonmetallic
9. Determining microbial effects on corrosion (cont.)	Use a different container material. The material could be changed to one with lesser susceptibility to microbiologically influenced corrosion (MIC). The degree of susceptibility will be dependent on the strains and population sizes of organisms postulated and cannot be predicted. There are no materials that could be said to be reliably immune	X	X	X
	Increase the heat and radiation output of the waste package to reduce the microbe population	X	X	X
10. Demonstrating long-term materials stability	Use a different container material. The material could be changed to a less highly alloyed, more predictable material (e.g., pure copper)	X	X	X
	Use a different container configuration. The container design could be changed to a more conservative configuration (e.g., thicker wall), to accommodate uncertainties in property prediction. Other possible configuration choices would be a design such as a pressure vessel with load-bearing filler or else a monolith. These designs could better accommodate uncertainties in load-bearing capabilities of the container wall	X	X	X
11. Demonstrating container failure rate and its effect on radionuclide release	Select a different container material	X	X	X
	Select a different container design configuration	X	X	X

NOTE: This is a list of technical concerns and options that pertain to the waste package. See Section 7.5.1.2 for a complete list of technical concerns and options.

PST87-2005-8.3.4-56

These tasks will be performed and the results provided to the architect-engineer. The welding and nondestructive examination development activities, which support the carbon steel design of the pressure vessel concept, will be performed by the Salt Repository Project under a direct contract with the DOE.

Study plan contents will be reviewed and revised to ensure that needs are addressed. Needs will be identified through the integration of study results into the design effort.

This study will provide data and physical components to be used in performance assessment activities, conceptual models, and qualification testing. Conceptual models that will be influenced by the products of this study include material characterization, packing performance, reliability assessment, performance sensitivity, and performance and reliability

The tests to be used in this study and an abbreviated description of the test method with the associated relevant parameters which will be produced are shown in Table 8.3.4.4-5. Tests will be conducted at postulated repository temperatures, using artificially aged materials. The technical procedures that will be followed as well as the test locations and number of tests to be conducted are shown in Table 8.3.4.4-6. The number of tests to be performed will be controlled by the required reliability as determined by the waste package design for reliability methodology development activity. This study will use the analysis and associated methods as shown in Table 8.3.4.4-7.

The three principal phases of the study are (1) laboratory tests, (2) scale-model container fabrication in simulated hot cell conditions, and (3) prototype fabrication in a hot cell simulator. Activities associated with these phases are identified in Table 8.3.4.4-8.

During Phase 1, for the SCP conceptual design container design development, the Salt Repository Project will evaluate commercially available welding and nondestructive examination processes to determine the technical and economical feasibility of using these processes with the base metals designated for that design. The criteria of the container design and construction standard (Section 8.3.4.4.2.3.3) will be applied in the evaluations.

Study information transferred to the architect-engineer will be used to support the design effort.

During Phase 1 for the bimetallic container development, the study will evaluate material combinations and processes for joining those materials and methods of joining the container components, assembling the container remotely, and examining the assemblies.

Table 8.3.4.4-5. Test methods and parameters (sheet 1 of 2)

Test title	Abbreviated description of test method	Relevant parameter(s)
Creep rupture tension test	Specimens are heated to an elevated temperature and subjected to a load	Creep response
Dimensional profile	Dimensional measurements	Cylindricity
Surface roughness	A profilometer is used to measure surface roughness in microinches	Surface texture
Heat transfer		Thermal conductivity
Empirical data		Specific heat
Empirical data	N/A	Modulus of elasticity
Compression test	Compress specimen until yield point is reached	Compression strength ultimate
Tensile strength test	Specimens are pulled to failure in tensile test machine	Tensile strength ultimate
Yield strength test	Specimens are pulled to point of yielding in tensile test machine	Yield strength
Shear strength test	Specimens are sheared in dies. Force/unit area required to shear is measured	Shear strength
Impact strength test	Impact load specimens having induced stress rises, and measure absorbed energy	Impact strength
Empirical data	N/A	Coefficient of thermal expansion
Density		Density
Plain strain fracture toughness		Plain strain fracture toughness
Tensile test		Total elongation
Tensile test		Uniform elongation
Tensile test		Reduction of area
Brineil, Vickers, Rockwell		Hardness
Brineil, Vickers, Rockwell		Rupture modulus
Brineil, Vickers, Rockwell		Poisson's ratio
Brineil, Vickers, Rockwell		Thermal diffusivity
Brineil, Vickers, Rockwell		Thermal expansion

PST87-2005-8.3.4-58

Table 8.3.4.4-5. Test methods and parameters (sheet 2 of 2)

Test title	Abbreviated description of test method	Relevant parameter(s)
Impact test		Nil-ductility
Impact test		Probability of defect detection
NDE, optical macro examination		Size of defect in container
NDE, optical macro examination		Void fraction in container
NDE, optical macro examination		Container strain

N/A = Not applicable.

NDE = Nondestructive examination.

PST87-2005-8.3.4-58

During Phase 1 for the filler material development, the study will evaluate the materials to be used, the form the material is to be used in, the availability and the use of that material in that form for hot cell use, and the processes for adding the filler to the container. The filler material will be selected with consideration for its compatibility with the container closure method, closure design, and closure processes. The filler material will also be evaluated for physical (mechanical) interactions and compatibility with the container, packing material and waste form.

At the completion of 30% advanced conceptual design, the architect-engineer will select the base metal, weld process, and nondestructive examination combinations that have exhibited optimal results during phase one testing. Other options will be dropped from future consideration. During Phase 2, container design development, and scale-model weldments that represent closure configuration, material, and joint design will be fabricated using the selected weld and nondestructive examination processes. The demonstration welds will be performed and inspected using simulated hot cell conditions (i.e., limited manual contact).

Also during Phase 2, the container study will incorporate the information developed by the filler material development study. This information will be used to demonstrate the practicality of the filler being added to the container during scale-model fabrication.

During Phase 1, the portion of the study responsible for the hot cell test facility will begin design activities and early in Phase 2 will place orders for all long-lead equipment. This design activity will reflect the needs of the site facility design which will have started at the beginning of advanced conceptual design by the architect-engineer. The design of the test facility will provide the basis for the final design of the site facility.

Table 8.3.4.4-6. Technical procedures, number, and location of tests

Test title	Technical procedure	Test location and number of tests
Creep rupture tension test	ASTM E 150	Container material Number TBD by reliability
Dimensional profile	To be developed	Container cylinder surfaces Number TBD by reliability
Surface roughness	To be developed	Container cylinder surfaces Number TBD by reliability
Heat transfer	ASTM E 457	Container material Number TBD by lot size and reliability
Compression test	ASTM E 209	Container material Number TBD by reliability
Tensile strength test	ASTM E 21, ASTM E 8	Container material Number TBD by reliability
Yield strength test	ASTM A 370	Container material Number TBD by reliability
Shear strength test	ASTM E 229	Container material Number TBD by reliability
Impact strength test	ASTM A 673, ASTM A 370, ASTM E 208	Container material Number TBD by reliability
Density	ASTM B 212	
Plan strain fracture toughness	ASTM E 399	
Hardness Vickers	ASTM E 92	
Hardness Rockwell	ASTM E 18	

TBD = To be determined.

PST87-2005-8.3.4-59

Table 8.3.4.4-7. Analysis, method of, and information produced

Analysis	Analysis method	Information gained
Waste Container Integrity	Mechanical models Empirical models GOETHER SINDA/TSAP EQ3/EQ6 ABACUS CHAINT ORIGIN2	Exposure limits (other to be added)

PST87-2005-8.3.4-60

Table 8.3.4.4-8. Major activities associated with the pressure vessel container development study

Title	Content
Laboratory weld and nondestructive examination (NDE) tests	<ul style="list-style-type: none"> • Weld samples (mechanical and corrosion tests) • Filler material development • NDE data • Material screening • Data to facility design
Scale model demonstration including welds and NDE	<ul style="list-style-type: none"> • Weld samples (mechanical and corrosion) • Material handling data • Design hot cell test facility • Procure long-lead facility equipment • NDE process and procedure refinement • Data to facility design • Construct test facility
Prototype construction	<ul style="list-style-type: none"> • Weld and NDE process and procedures • Remote facility construction completed • Vessel qualification to design standard • Remote handling and process equipment • Fabricate prototypes • Site facility design

PST87-2005-8.3.4-61

Beginning with the 30% license application design, one design will be chosen and fabricated as a prototype during Phase 3 activities. This fabrication will take place in the hot cell test facility prototype. All other designs will be dropped when this selection is made. The activities associated with the fabrication of the prototype will take place as soon as the selection has been made.

The hot cell test facility will simulate hot cell conditions relative to remote operations for production and maintenance. A qualified vendor will manufacture, inspect, and supply all necessary components for the prototypic containers (shell, ends, lifting attachment, etc.). A qualified vendor will assemble and inspect all of the components of the container except for the loading of the simulated fuel and the closure of the container. Test facility equipment and capabilities include the following:

- Remote container handling and head placement.
- Fixture for rotation of container or welding equipment.
- Application of appropriate preheat to the weld area.
- Remote placement of filler material.
- Remote replacement of welding consumables.
- Remote control of welding parameters.
- Remote placement and control of postweld heat treat equipment (if needed).
- Remote application and control of nondestructive examination.

Prototypic containers will be provided to the waste package program to support qualification and handling and safety testing activities. Hot cell design development and data from the prototypic container tests will be provided to support the design. This information will be applied to support the container and site facility design efforts.

8.3.4.4.3.2 Monolith container development study.

The monolith container development study will be performed to:

- Provide information relative to the waste package system and subsystem design effort.
- Determine the ease of fabrication of candidate container materials.
- Develop the most cost effective and reliable container component fabrication processes.
- Develop the container closure configuration and processes.

- Develop the container assembly fabrication processes.
- Identify the quality control examination processes to be used.
- Design and construct a prototypic hot cell fabrication facility.
- Produce prototypic containers to be used for testing.
- Address technical concerns and needs identified in Section 7.5.

These tasks will be performed by the study and provided to the integrating contractor and the architect-engineer.

The integrating contractor will assure that the study provides information needed by the architect-engineer during the phases of advanced conceptual design and license application design (Section 8.3.4.4.3.3.2). Study plan contents will be reviewed and revised to ensure that the needs of the project are addressed. Needs will be identified through the integration of study results into the design effort.

This study will provide data and physical components to be used in performance assessment design activities, conceptual models, and qualification testing. Those conceptual models influenced by the products of this study include material characterization, packing performance, reliability assessment, performance sensitivity, and performance and reliability.

The monolith concept relies on the hot isostatic pressing process to produce a monolithic type structure. This fabrication process consists of subjecting the assembled container to high pressures while at high temperatures to cause densification and diffusion bonding. The fabrication process begins with filling a container containing spent fuel with a powder. The powder is compacted by vibration or other means to a density of approximately 80% and (if needed) conditioned with wet hydrogen and argon to reduce surface oxides and to facilitate the bonding process. After conditioning, the end cap is installed, and the container is evacuated. Joints between the cap and the container shell are conditioned and sealed. The hot isostatic pressing process is applied to the evacuated assembly, which, in the case for the copper monolith, is heated in argon gas to approximately 500 °C and pressed at approximately 152 MPa (1,500 atm). The result is a solid matrix of copper that has diffusion bonded into a fully densified seamless mass, completely surrounding the fuel elements.

Those tests to be used in this study and an abbreviated description of the test method with the associated relevant parameters which will be produced by the tests are shown in Table 8.3.4.4-5. The technical procedures that will be followed as well as the test locations and number of tests to be conducted are shown in Table 8.3.4.4-6. The number of tests to be performed will be controlled by the required reliability as determined by the waste package design for reliability methodology development activity.

This study will use the analysis and associated methods as were shown in Table 8.3.4.4-7.

The three principal phases of the monolith container development study are (1) laboratory test to resolve uncertainties and develop weld and non-destructive examination processes and procedures, (2) scale-model monolith fabrication demonstration in simulated hot cell conditions, and (3) prototypic preparations in simulated (nonradioactive) hot cell conditions. Activities associated with these phases are summarized in Table 8.3.4.4-9.

Material screening will take place during Phase 1. Although copper is the initial material for the monolith container concept, steel, Cupronickel 90-10, and bimetallic combinations will be considered. The final materials to be included in the development will be identified by the architect-engineer.

Uncertainties associated with the hot isostatic pressing process consist of powder selection, waste form interaction, powder cleaning, joint closure design, and weld and nondestructive examination process and procedures. Powder size and grade affect bonding and product density; powder cleaning by oxide reduction at elevated temperature affects strength. Weld and nondestructive examination processes affect joint design and may have an effect on quality. These items will be addressed during Phase 1 to support the 30% advanced conceptual design phase.

Table 8.3.4.4-9. Major activities associated with the monolith container development study

Title	Content
Laboratory weld and nondestructive examination (NDE) tests	<ul style="list-style-type: none"> • Weld samples (mechanical and corrosion tests) • Closure leak tightness and quality • NDE process and procedure data • Material screening • Data to facility design
Scale model demonstration including welds and NDE	<ul style="list-style-type: none"> • Weld samples (mechanical and corrosion) • Material handling data • Design hot cell test facility • Procure long-lead facility equipment • NDE process and procedure refinement • Data to facility design • Construct test facility • Hip powder selection • Closure process and procedure • Cleaning and oxidation processes
Prototype construction	<ul style="list-style-type: none"> • Weld and NDE process and procedures • Remote facility construction completed • Vessel qualification to design standard • Remote handling and process equipment • Fabricate prototypes • Site facility design

PST87-2005-8.3.4-62

The nondestructive examination techniques addressed in Phase 1 include the ultrasonic and the radiographic processes. Both processes will be used to evaluate the container before closure and the closure joint after closure. Ultrasonic beam scatter will be evaluated because of material grain size effects. Neutron radiation radiography will be evaluated as a potential nondestructive examination process because of the possible adverse effects of the waste form radiation on conventional radiographic processes.

During Phase 2, activities which will support the 60% advanced conceptual design phase, including the hot isostatic pressing process and closure and nondestructive examination processes selected during Phase 1, will be applied to fabricate scale-model demonstration containers. The integrating contractor will perform corrosion testing of samples representative of the demonstration containers, and the architect-engineer will apply the results in the container design.

Beginning in Phase 1, the hot cell test facility design activities will begin, and early in Phase 2, orders will be placed for all long-lead equipment. This design activity will reflect the needs of the site facility design, which will have started design at the beginning of advanced conceptual design. The design of the fabrication test facility will form the basis of the final design of the site facility.

At the end of 30% license application design, one design will be chosen and fabricated as a prototype during Phase 3 activities in the prototypic hot cell test facility. All other designs will be dropped when this selection is made. The activities leading to fabrication of a prototype will take place as soon as the selection has been made. The fabrication test facility will simulate hot cell conditions relative to remote operations and maintenance. A qualified vendor will manufacture, inspect, and supply all necessary components for the prototypic containers (shell, ends, lifting attachment, etc.). A qualified vendor will assemble and inspect all of the components of the container except for the loading of the spent fuel and the closure of the container. Test facility equipment and capabilities include the following:

- Remote container handling set up and operation.
- Fixture for rotation of container or welding equipment.
- Remote replacement of welding consumables.
- Remote control of welding parameters.

Prototypic containers will be provided to the waste package program to support qualification testing and handling and safety testing activities. Fabrication facility design development and data from the prototypic container tests will be provided to support the container design and site fabrication facility design efforts.

8.3.4.4.3.3 Container handling and safety testing study.

The purpose of this study is to obtain confirmatory experimental data on the ability of the container to properly interface with the facility equipment. Additionally, the study will verify that waste package safety requirements have been met, such as the ability of the container to withstand an accidental drop.

The test program is defined only to the general planning level. The design of the testing program will be accomplished at the conclusion of the advanced conceptual design, and testing will be completed during license application design. These tests will be designed to demonstrate container effectiveness in both normal and off-normal conditions.

Testing will start at the end of the 30% phase of the license application design. At that point, the final design concept will have been selected and the component manufacturing processes will have been developed. Once the design has been selected and prepared, components will be fabricated and the tests conducted. The work will be scheduled for completion in time to support the issue-for-approval license application design task and subsequent external review cycle.

These tests are being conducted to support the resolution of Issue 2.6 as well as any site-specific requirements (to be developed) for handling and safety operations in the facility. Conditions that will be evaluated during the preparation of the detailed test plans and procedures include facility-specific drop heights, postdrop acceptance criteria, container test conditions, and acceptance criteria.

This study does not include testing of the container in routine handling operations such as lifting, upending, shipment, emplacement, and retrieval because this work is covered by other test programs repository waste handling studies. The waste package function for these tests is limited to supporting the test results as they apply to the components under waste package responsibility.

8.3.4.4.3.4 Nonmetallic container development study.

The purpose of this study is to assess the technical feasibility of using a nonmetallic (composite, coated, etc.) container for a repository in basalt. Given technical feasibility, a preliminary design and related cost and schedule impacts of using such a container will be developed.

This study is included in the containers investigation as an alternate to the metal containers being developed in the two other container studies. The objective is to develop sufficient data to support the development of a detailed design and fabrication development and demonstration program if, and when, the metallic containers are determined to be unlicensable.

The selection of a nonmetallic container concept will have a major impact on the entire program. Major modifications to the waste package design and development investigation will be required if this concept is utilized. Likewise, major modifications will be required by the materials characterization program (in areas such as corrosion tests and container packing interactions), performance modeling, and reliability allocations. A nonmetallic container will result in revised waste package component handling scenarios. This will cause changes in the facility, both above and below the surface. This study does not address these aspects but is limited to the feasibility study and related technical, cost, and programmatic impacts. This information will be generated by working in cooperation with the integrating contractor and the architect-engineer.

The study is currently limited to theoretical investigations. No demonstration hardware is currently included in the scope of the study; although, as both this and the metallic studies progress, the scope of this plan may be revised.

This study will be divided into four general phases of work: (1) candidate material selection, (2) manufacturability assessment, (3) design and reliability assessment, and (4) preparation of a detail plan for development (for use if the nonmetallic container approach is selected).

Phase 1 will identify suitable materials that can be expected to perform to the required level and are deemed practical from a manufacturing perspective in the sizes and configurations appropriate for a container. (Configuration options will not be limited to the four pressurized water reactor/nine boiling water reactor configurations studied for metal containers.) This activity will be accomplished by using available literature and expert judgment.

Given the results of the material screening, manufacturability testing and analysis will be performed during Phase 2. Technical concerns such as size limitations, geometric shape possibilities, tolerances, manufacturing reliability, quality control, availability of raw materials, and the impact to the facility and handling equipment will be evaluated. Initial data for inclusion in the project life cycle cost models will be developed.

Assuming the nonmetallic container design remains a promising contender, a design study for a waste package subsystem using a nonmetallic container will be initiated during Phase 3.

Detail planning to this study will be performed assuming that the non-metallic container concept is selected. The plan will provide the necessary updates to the overall waste package program as well as related activities, such as the facility design activities. Major impacts to the waste package program schedule are likely to result from the decision to use a nonmetallic container and this draft plan will form the basis for reprogramming the baseline program.

Activities associated with these phases are summarized in Table 8.3.4.4-10.

Table 8.3.4.4-10. Major activities associated with the nonmetallic container development study

Title	Content
Candidate material selection	<ul style="list-style-type: none"> • Literature search for material selection • Initial material selection • Screen material based on performance
Manufacturability feasibility	<ul style="list-style-type: none"> • Identify fabrication processes • Perform feasibility analysis • Assess material performance • Develop container design • Nondestructive examination process and procedure
Design and reliability assessment	<ul style="list-style-type: none"> • To be determined if the nonmetallic container is selected
Preparation of follow-on plan	<ul style="list-style-type: none"> • To be determined if the nonmetallic container is selected

PST87-2005-8.3.4-63

8.3.4.4.4 Application of results

The investigation results will support activities in the waste package and repository programs.

In the waste package program, information from the investigation will be applied in the container design. In the repository program, information will be applied to the facility design (e.g., hot cell, handling, welding, and nondestructive examination equipment design).

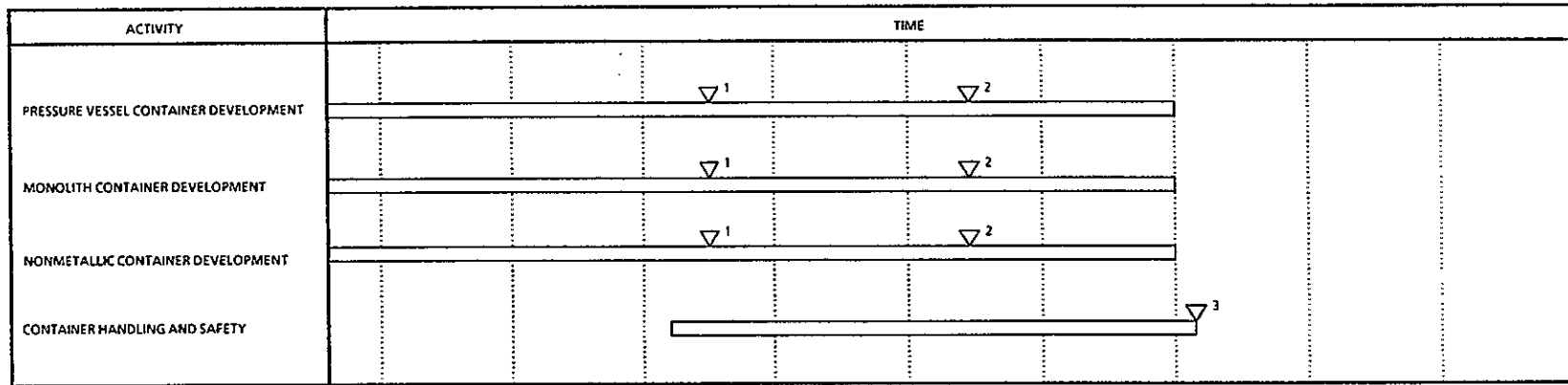
Study information will be applied to characterize processes and parameters that are applied in the design process. Mechanical and metallurgical parameters will be characterized and applied to assure that the container strength is adequate.

8.3.4.4.5 Schedule and milestones

The studies contained this investigation will commence activities at the same time the advanced conceptual design starts. Major milestones and associated time phasing are shown in Figure 8.3.4.4-3.

8.3.4.4.5 Packing development investigation

The waste package is being developed to satisfy the two major NRC criteria of substantially complete containment for 300 to 1,000 yr (Issue 1.4, Waste Package Containment) and long-term control of radionuclide release



PS&B-2014-03A-9

- ▽¹ INITIAL SCREENING TO REDUCE CONTAINER CONCEPTS AND OPTIONS FOR FURTHER STUDY.
- ▽² FINAL SELECTION OF CONTAINER CONCEPT; SELECTED CONCEPT WILL BE FABRICATED AS A PROTOTYPE
- ▽³ ISSUE TEST REPORT.

Figure 8.3.4.4-3. Container development investigation.

(Issue 1.5, Release Rate). As a major component of the waste package system, the packing is also required to assist in satisfying these two major criteria. Consequently, the functions of the waste package packing are outlined as follows:

- Provide a physical and chemical environment to help minimize container corrosion during the 1,000 yr following repository closure, during which substantially complete containment of radionuclides is required. Secondary functions include
 - (a) minimization of groundwater flux past the container and
 - (b) removal of oxygen as a potential corrosive agent.
- Control transport of radionuclides from the waste package during the 1,000 yr containment period in the event of premature container failure.
- Minimize long-term radionuclide release from the waste package following the containment period. Other functions include
 - (a) minimizing mass transport from the waste package to the host rock, (b) establishing and maintaining a waste package groundwater composition that minimizes radionuclide solubility, and
 - (c) maximizing radionuclide sorption.

In addition to the regulatory criteria of 10 CFR 60 (NRC, 1987a), the preformed packing concept has been derived from three main considerations: (1) the characteristics of the basalt system, (2) the multibarrier concept, and (3) the need for engineering flexibility.

The engineering flexibility consideration is critical to the successful development of the preformed packing component primarily because of the evaluation of long-term (i.e., approximately 10,000 yr) performance demanded by regulatory criteria. To facilitate the engineering process, the packing composition variables must be flexible enough to (1) allow quantification of its material properties and performance of its assigned functions to the extent possible, and (2) provide reasonable and achievable design alternatives that can be applied if performance evaluations necessitate design changes.

8.3.4.4.1 Purpose and objectives

The overall goal of the packing design and development investigation is to provide specifications for the final waste package packing component. The specifications will be developed from experimental data and performance analyses that quantify the ability of the packing component to perform its assigned functions. Hence, the purpose of the packing development investigation is to support packing design and performance assessment by (1) generating packing components or bulk property data, (2) developing processes and procedures, and (3) testing prototypic packing under expected repository conditions.

More specifically, the studies supporting this investigation will provide technical information needed for developmental testing and assessment of packing prototypes to achieve the following objectives:

- Development of raw materials specifications (e.g., sodium-bentonite clay for fabrication, handling, and emplacement).
- Selection and optimization of materials.
- Development of fabrication processes and quality assurance procedures.
- Development of emplacement processes and quality assurance procedures.
- Development of packing design margin (i.e., tolerance).

Developmental testing and assessment activities to be undertaken include the following:

- Packing fabrication, packing nondestructive examination, and packing handling and emplacement methodologies and (or) equipment.
- Installation of measurement devices.
- Calibration and operation of development test equipment.
- Collection and analysis of data.

Periodic reports will provide input data to various design/performance analyses, with the ultimate use being to prepare waste package design specifications for packing materials.

8.3.4.4.5.2 Rationale

The physical and chemical properties of emplaced packing materials will be engineered to provide container protection (i.e., retard ingress of groundwater to and control the flow past the container, thus minimizing container corrosion during the waste package lifetime) and to minimize radionuclide transport by groundwater. Establishing and maintaining a favorable environment is essential for the postclosure periods. In addition, the physical and chemical properties of the packing will be engineered to control radionuclide migration after the container has breached. The mechanisms for the packing radionuclide isolation performance are the chemical reactivity of the packing materials with radionuclides and the physical properties that control migration by diffusion only. The most effective method to accomplish these requirements is to ensure that a favorable physical and chemical environment is maintained that minimizes radionuclide migration through the waste package packing materials.

Preliminary goals for the packing, developed by a performance allocation process, are discussed in Section 8.2.2 and detailed in the Issue Resolution Strategies for Issues 1.4 and 1.5. The performance goals addressed, in part, by the Packing Development Investigation are summarized in Table 8.3.4.4-11.

The emplaced packing physical properties of greatest importance in minimizing groundwater flow are as follows:

- Swelling pressure capability.
- Hydraulic conductivity.
- Strength characteristics (bearing, compressive, tensile, and shear).

8.3.4.4.5.2.1 Current concept for packing.

The NRC definition of a waste package in 10 CFR 60 (NRC, 1987a) includes packing material as a component. For a nuclear waste repository in basalt, the current reference design packing comprises a mixture of crushed basalt and bentonite (75:25 by weight). In the current design concept the packing is preformed into highly compacted shapes (approximately 2.0 g/cm^3 (125 lb/ft^3)), which form a cylindrical shell approximately 15 cm (approximately 6 in.) thick that encloses the waste container. The bentonite ensures the low permeability of the packing because of its swelling properties and naturally low permeability. In addition, basalt and bentonite are highly sorptive materials. Basalt provides the chemical reactivity to condition the groundwater such that low solubilities of multivalent radionuclides are achieved.

8.3.4.4.5.2.2 Alternate packing materials.

Although the preformed packing units satisfy all the basic requirements, functions, and design criteria as a major component of the waste package system, it may be possible to find similar materials and placement methods more cost effective and satisfactory. Some of the clay minerals (e.g., illite, kaolinite) may be suitable as packing materials to satisfy the performance issues.

Literature review and preliminary testing of these materials to find possible alternatives will be investigated. Similarly, methods such as using preformed packing units in combination with pneumatically transferred packing or filled and tamped packing will also be studied.

8.3.4.4.5.2.3 Testing methodology.

The packing development studies and tests described in the testing methodology for this investigation (Fig. 8.3.4.4-4) are developmental and specific to waste package packing design, materials fabrication processes and quality assurance, and preformed packing handling and emplacement. Evaluation of preformed packing performance will be accomplished by a combination of laboratory tests, large- or full-scale experimental work, and modeling analyses. Experimental work is concentrated in three major areas: equipment development, physical property experiments, and data reduction. The physical properties of preformed packing are important in the evaluation of both the minimization of corrosion (Issue 1.4) and radionuclide mobility (Issue 1.5).

Table 8.3.4.4-11. Packing development investigation parameters and goals

Subsystem component	Component function	Performance parameter	Tentative parameter goal	Needed confidence	Expected values	Current confidence	Information need
Packing*	Limit mass transport	Hydraulic conductivity	$<10^{-6}$ cm/s	High	10^{-6} to 10^{-10} cm/s	Moderate	Packing fabrication
		Swelling pressure	<3 MPa	Moderate	0.1 to 0.5 MPa	Low	
	Resist plastic deformation	Shear strength	30 KPa	Moderate	10 to 40 KPa	Moderate	
		Creep rate	TBD	Moderate	TBD	N/A	

*Altered packing at expected conditions.

PST88-2014-8.3.4-3

8.3.4.4-49

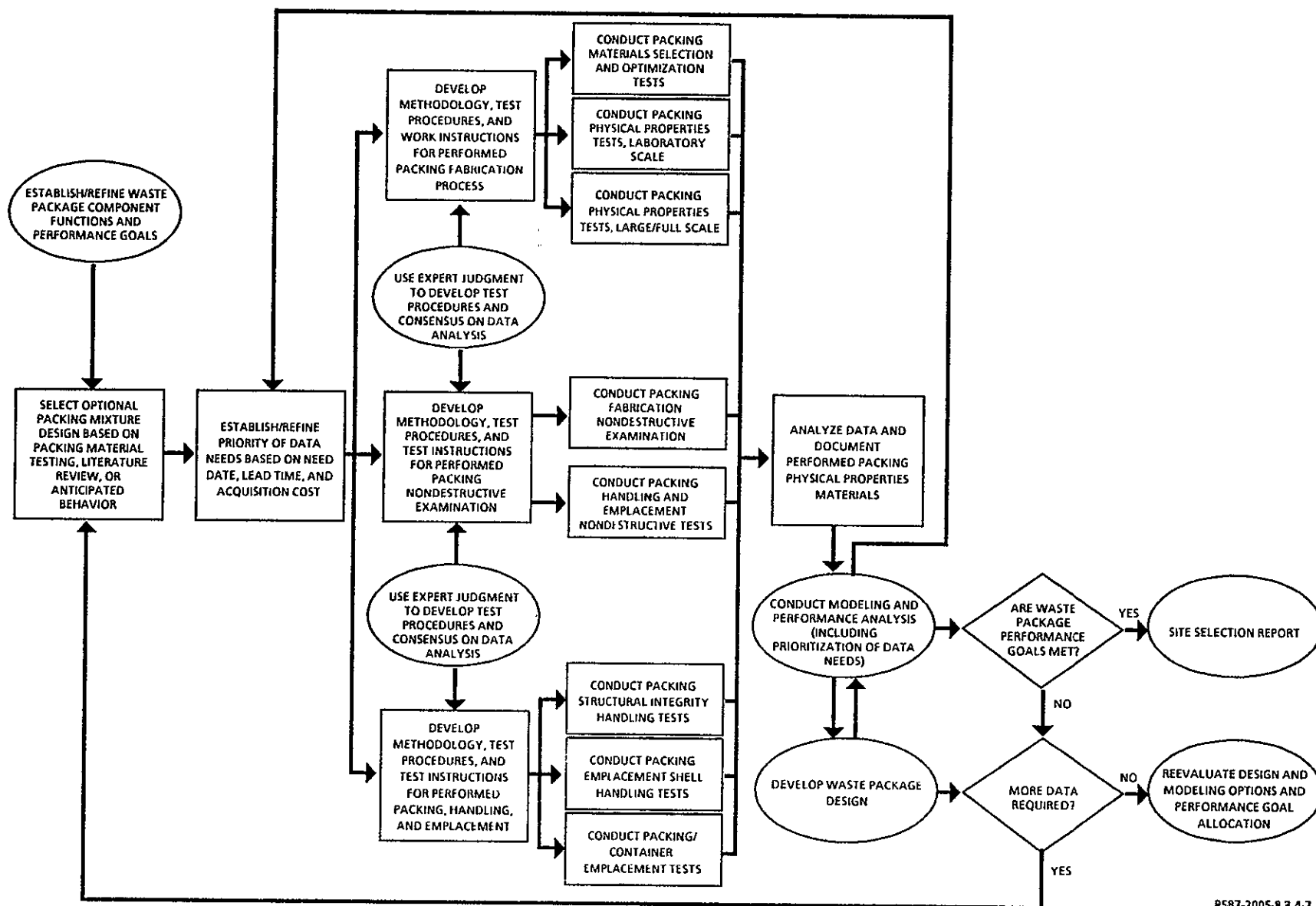


Figure 8.3.4.4-4. Packing development investigation methodology.

P587-2005-8.3.4-7

CONSULTATION DRAFT

The general process of testing the physical properties of preformed packing is to develop the appropriate experiments, generate the data base, and evaluate the data. As shown in the testing methodology (Fig. 8.3.4.4-4), evaluation of the data leads to one or more of three basic decisions, which include the following:

- Providing the data as input to waste package design or performance analyses.
- Generating a more extensive data base of the same type of data.
- Identifying a new type of data and accompanying test procedures that must be generated as a result of the preceding data evaluation.

It is important to note the use of working hypotheses to generate and evaluate data validity (i.e., the scientific method) requires the continuous input of expert judgment. The physical properties test data developed through the testing methodology will be evaluated against the information needs defined in Table 8.3.4.4-12.

Table 8.3.4.4-12. Information needs to be satisfied by the packing development investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern (see Section 7.5)
Title	Abbreviated description		
Fabrication of packing	Packing composition properties, and fabrication methods are needed	Develop packing designs that meet the hydraulic conductivity goals to limit transport to diffusion controlled processes and have sufficient strength to maintain waste package configuration	Issues 1.4 and 1.5 Technical concerns: 1, 2, 3, 5, 6, 8, 12, 13, 14, 15
Nondestructive examination (NDE) of packing	NDE testing methods that will define and evaluate the integrity of the packing are needed	Use packing physical properties data to validate performance assessment model predictions	
Handling and emplacement of packing	Packing, storage, handling, and emplacement techniques are needed	Use packing physical properties data to validate performance assessment model predictions	

PST87-2005-8.3.4-39

Using packing material data, predictive models will be refined to better improve the understanding of pressure/temperature regimes and the state of groundwater in the packing. If the assumptions, estimates, or expectations that underlie the packing development testing prove to be invalid (e.g., if it becomes apparent that chemical and radionuclide changes (alteration) will seriously affect packing swelling and permeability), the waste package designs will be updated to incorporate the additional information. Several waste package design options are available, if necessary, to improve preformed packing performance.

Other packing design options have been identified as part of the technical concerns identified in Section 7.5.3. These options include:

- Adding a reductant such as steel shot to the packing to help maintain the proper redox conditions.
- Using a different waste package emplacement configuration such as in-room emplacement, which could use packing emplaced pneumatically or mechanically tamped in place.
- Changing the packing thickness.
- Changing the packing composition.

The effects of these design options are discussed in the description of the studies in Section 8.3.4.4.5.3.

Hydraulic conductivity, swelling pressure/capacity, strength, and thermal expansion data are to be collected for preformed packing materials and the optional designs as a function of clay density, clay-to-basalt ratio, particle-size distribution, temperature, and moisture content. In addition, the effects of dehydration, steam treatment, hydrothermal alteration, and groundwater flow on these physical properties also will be evaluated. These data will be used to validate data developed from laboratory-scale testing of the packing material.

Constraints on packing development testing include limits on the ability to accelerate many of the processes and reactions that must be observed. To deal with schedule and resource limitations, methods must be developed to deal with low-hydraulic conductivities that lead to long saturation times when tests involve large-scale and high-density specimens. Many of the test activities will be long-term activities, and this constraint will impose performance reliability problems with related instrumentation.

A generic constraint that will affect packing development is obtaining reference case information in a timely manner, which in this case includes results of waste package design engineering/trade studies, design requirements, and packing materials specifications. This information is a prerequisite to identifying the specific test requirements.

Another constraint is that preliminary studies indicated that a large number of parameters must be considered over a wide range of repository conditions. Therefore, several tests need to be performed to satisfy and resolve specific waste package issues. However, the required test parameters will be identified through the process of performance allocation. This process will be designed to assure that the data and information base will meet all NQA-1 (ANSI/ASME, 1986) requirements and support the licensing application for the repository.

8.3.4.4.5.3 Description of studies

The following subsections describe the three studies planned for the packing development investigation: (1) packing fabrication, (2) packing nondestructive examination, and (3) packing handling and emplacement. Specifications for preformed packing in the final waste package design will be developed from experimental and performance analyses that quantify the ability of the packing to perform its assigned functions.

8.3.4.4.5.3.1 Packing fabrication study.

The objectives of this study are to determine the optimum basalt/bentonite mixture, fabrication and batching technique to be employed, and physical properties of prototypic packing (preformed and other emplacement techniques). The packing materials will be engineered to provide container protection during the waste package lifetime and to minimize radionuclide transport by groundwater.

The data from this study will provide information to guide the design activities of the waste package and provide input to the performance assessment model. The results from this study also will be used to verify laboratory data from the packing materials testing activities and develop specifications for the final waste package packing components design. Tests to be described in more detail in the following sections are summarized in Table 8.3.4.4-13. Also included are parameters to be evaluated and the data to be produced from each test.

Three areas associated with packing fabrication process development will be studied: (1) materials selection and optimization will determine the optimal packing mixture, recommend the fabrication and batching process, and, for preformed packing, determine the packing unit mold configuration. The objective will be to determine the feasibility of fabricating the current reference preformed packing or, if needed, optional fabrication methods in a full-scale production operation; (2) physical properties data of laboratory-scale packing materials will be determined at ambient and expected repository in situ conditions. The tests will develop a materials data base for packing and will validate laboratory data from the packing materials testing activities; (3) physical properties of packing materials also will be tested on a large (full) scale, at expected in situ conditions, to validate previous laboratory testing.

8.3.4.4.5.3.1.1 Materials selection and optimization tests. This testing area will develop data that will lead to the selection of the optimal mixture, fabrication and batching process, and packing unit mold configuration for preformed, pneumatically emplaced, or mechanically tamped packing. Packing mixture optimization tests will be performed to determine an optimum combination of basalt size and distribution, clay content, moisture content, and compaction method required to produce a packing material with a target minimum dry density of 2.0 g/cm^3 (125 lb/ft^2) (for the preformed packing elements). Tests will be designed after ASTM standards (i.e., ASTM 698-78, ASTM D 2166-66) and other applicable standards.

The optimum basalt gradation for the packing mixture will be determined by performing moisture-density tests on basalt mixtures of various particle sizes and gradations, in the absence of bentonite. From the test results, a graph of dry density versus moisture content for each gradation will be produced. The mixture exhibiting the highest dry density will be selected as the standard basalt mix for further testing with bentonite.

Moisture-density tests will then be performed using basalt/bentonite mixtures with varying clay content and moisture content. These tests will evaluate three different compaction techniques (i.e., tamping, vibration, and static pressing). The amount of particle breakage that can occur with each of the fabrication techniques will also be evaluated, since particle breakage will change the basalt gradation and could alter the performance of the mixture.

Unconfined compression tests will be performed on air-dried samples to determine their compressive strength. Because all packing physical properties are directly related to or controlled by density and compressive strength, the selection of the optimum packing mixture and compaction technique will be based on the results of moisture-density and compressive strength tests.

The relative merits of air drying versus controlled drying, as well as drying time, will be evaluated to determine the optimum curing technique (process) to be employed in full-scale packing production. The compressive strength will be determined for packing material specimens of a specific mixture and moisture content that have been air and controlled dried. The curing technique (process) that yields the maximum compressive strength will be identified.

The suitability of various types of batching techniques (i.e., stirring and kneeling) and equipment to support the production of full-scale packing elements or optional emplacement configurations will be investigated by reviewing available and practical processes, performing laboratory testing, and evaluating the effect on the fabrication process and selected physical properties.

Compressive strength tests will be performed on test specimens that have been produced from various mixing techniques and equipment. The method of compaction used will be common to each of the tests. The standard deviation of test data will determine the effectiveness of each of the mixing techniques considered. It will be important to investigate the amount of particle

Table 8.3.4.4-13. Summary of tests in packing fabrication study

Test title	Abbreviated description	Relevant parameters
Moisture-density test	Specimen is placed in a mold and compacted in three layers of approximately equal height. Compaction is accomplished by tamping, static pressing, or vibrating depending on the method under investigation. After compaction, dry density and moisture content are determined.	Density
Unconfined compression test	An axial strain or stress is applied to the specimen at a constant rate. The loading is increased until failure results. Deformation and load are recorded.	Shear strength
Splitting tensile strength	The specimen is placed on its side in a bearing block. A compressive load is applied to the side of the specimen. Loading is increased until failure results.	Shear strength
Triaxial shear strength	An axial load is applied to a confined sample in the triaxial cell at a constant load or strain. The load or strain is increased by increments until the specimen fails.	Shear strength
Constant head permeability test	Perform test in constant-head permeameter. Measure volume of water passing through packing in a certain time interval.	Hydraulic conductivity
Creep test	Specimen is loaded with a compressive force of about 40% of its compressive strength. Strain is recorded at certain intervals for a period of 1 yr.	Creep rate
Swelling pressure test	The specimen is placed in the triaxial cell. The swelling pressure is measured by recording the increase in confining pressure required to keep the sample volume constant in both axial and lateral directions.	Swelling pressure
Thermal conductivity test	A thermal needle, which contains a heat source and thermocouple, is embedded in a 10.2-cm (4-in.) diameter sample. Heat is applied at a constant rate and the line temperature is measured as a function of time.	Thermal conductivity
Los Angeles abrasion test	Particles of the packing material are placed in the testing device. The drum of the device is rotated for 500 revolutions. The material is removed and sieved to measure the percent lost.	Wear resistance

PST87-2005-8.3.4-40

breakage that can occur with each of the batching techniques, since this could alter the performance of the mix by changing the basalt gradation. In addition to batching technique, the mellowing period (i.e., time allowed between addition of water and compaction of material) will be investigated to determine the amount of time needed to optimize compaction of the packing material.

The bearing strength must be taken into consideration when determining the thickness of the packing. The thickness and composition of the packing must be sufficient to prevent container settlement. The thickness of the packing must also be sufficient to limit water and radionuclide migration. Therefore, for preformed packing, the unit mold configuration also will be dependent on data received from container settlement testing and packing handling and emplacement development tests.

The joint between preformed packing elements must be fabricated to ensure that permeability and sorptive characteristics of the packing are not compromised. Conceptual designs reflecting various possible joint configurations will be evaluated. In considering the joint configurations, the feasibility of incorporating the joint concepts into the packing fabrication process and the packing emplacement process will be studied and tested. Since much of this testing cannot be quantified, decisions will be based on laboratory observation. Once a joint concept has been selected, the effectiveness of the concept with regard to permeability will be demonstrated by performing hydraulic conductivity tests both across the joint and in the plane of the joint. The results of these tests will identify an optimum joint concept.

8.3.4.4.5.3.1.2 Physical properties--laboratory-scale tests. Laboratory tests will be performed to determine the physical properties of packing using the optimal fabrication and batching techniques determined in the materials selection and optimization study area. The results of these tests will be used to guide the waste package design as input to the performance models and to validate laboratory data from the packing material testing activities. The packing physical properties that are important to container life and radionuclide release rates can be broken into four categories: (1) hydraulic conductivity, (2) swelling pressure, (3) strength, and (4) thermal conductivity. The physical properties will be determined from full-scale packing core samples fabricated by the reference and alternate techniques. These physical properties will be tested at ambient and expected repository in situ conditions with altered packing over the range of variability expected in the bentonite and basalt composition. If the laboratory-scale test results indicate that temperature and pressure have little effect on the physical properties, the packing material will not be altered before large-scale (prototypic) testing. Tests will be repeated to establish the reproducibility of the test results.

Hydraulic conductivity data will be used to predict the ability of the packing material to maintain low permeabilities. This data will be used as input to the performance assessment model to predict the movement of water through the waste package and the release of radionuclides to the host rock.

The hydraulic conductivity test will be designed after constant head permeability tests (ASTM D 2434-68 and other applicable standards). Independent variables consist of radial and axial confining pressures, cracks in the packing material, and temperature. The dependent variables to be measured consist of the flow of effluent versus time.

Swelling pressure data will be used to predict the ability of packing material to fill void spaces from construction tolerances of the waste package or openings in the waste package caused by corrosion of the emplacement shell and container. Another important use for the swelling pressure data will be to determine if an upper limit on packing density and clay content is required to prevent damage to the waste container as a result of swelling of the packing. The swelling pressure/capacity tests will be designed after ASTM D 2434-68, ASTM D 2850-82, and other applicable standards. The independent variable to be manipulated will be the temperature. The dependent variables to be measured consist of pressure, hydraulic head, swelling pressure, and flow rate of water at the effluent side.

For preformed packing, strength data are important to ensure that the structural integrity of the packing material is sufficient to prevent damage during handling of the packing elements in order to prevent damage due to abrasion during installation of the waste container. Any of the packing designs must have sufficient long-term strength to prevent container movement after emplacement, and to prevent long-term creep from occurring. The properties that need to be determined consist of uniaxial compressive strength, splitting tensile strength, triaxial shear strength, coefficient of friction, Young's modulus, Poisson's ratio, and creep. All tests will be designed after ASTM standards with minor modifications made where required. Some tests will be adapted from ASTM standard soil-cement testing procedures when equivalent soil testing procedures have not been established. The independent variables to be manipulated consist of fabrication method, temperature, confining pressure, pore pressure, and moisture content (some of these variables may not apply to all strength tests). Dependent variables to be measured consist of load, strain, pore pressure, peak strength, and residual strength.

Thermal conductivity data are needed to predict temperatures in the waste package and repository as a function of time and location. This information is important because knowledge about the temperature is required for planning tests for all components of the waste package, disturbed rock zone, and emplacement rooms. The thermal conductivity tests will be designed after CRD-C-45-65, and other applicable standards. The independent variables to be manipulated consist of temperature, moisture content, and fabrication method. The dependent variables to be measured consist of temperature versus time.

Physical properties testing of packing samples with voids and other defects will be performed as an interface with nondestructive examination activities. This will help determine the accuracy of selected nondestructive examination methods and how the physical properties relate to the imperfections within the packing. Physical property tests intended to evaluate hydraulic conductivity,

swelling pressure, strength, and thermal conductivity will be correlated with nondestructive examination measurements of density, void content, porosity, cracking, and general uniformity. This information will contribute to the establishment of acceptance criteria for production testing.

8.3.4.4.5.3.1.3 Physical properties--large-or full-scale testing.

Large-scale or full-scale tests will be used to determine the physical properties for large- or full-scale packing samples in an effort to validate previous laboratory testing and provide specifications for final packing component design. The physical properties to be tested can be grouped into the following categories:

- Hydraulic conductivity.
- Swelling pressure/capacity.
- Strength.

All tests will be performed at expected repository in situ conditions.

Hydraulic conductivity tests will be conducted on an engineering-scale mockup of the emplaced waste package within an autoclave cell. The waste package mockup will have a full-scale cross section and the same weight per unit length as the waste package container. The proposed cell will be designed to simulate the waste container in the reference emplacement configuration. The engineering-scale mockup will use a porous liner to allow the outer surface of the packing material to be in contact with high-pressure synthetic groundwater. Packing material produced using the optimum mix, fabrication, and batching techniques selected will fill the volume between the simulated waste container and the porous liner. Electrical resistance heaters will be placed within the package mockup to simulate waste heat generation. Prior to testing, the packing material will be altered (if applicable) to simulate expected conditions of the packing at the start of resaturation. Hydraulic tests will be performed to measure the movement of water through the waste package, which will help to predict the resaturation time and the expected release of radionuclides from the waste package. Two independent tests will be run at a pressure of 9.3 MPa (1,350 lbf/in²). The first test will be conducted at 100 °C and the second at 250 °C. The proposed duration of each test is approximately one year.

Swelling pressure/capacity will be measured during the hydraulic conductivity test by measuring the strain of the waste container and porous liner due to the swelling of the packing material. This will be accomplished by placing strain gages at various points on the waste container and porous liner. Strains will be recorded periodically to determine swelling pressure trends. The data will provide an idea of the ability of packing material to fill void spaces and will help to establish if an upper limit on packing clay content and density are required to prevent damage to the waste container. Cracked or damaged packing from the packing handling and emplacement testing of preformed packing will also be investigated through laboratory observation to determine if the swelling capacity is great enough to give the packing material the ability to self-heal.

Strength tests will be performed at the conclusion of each of the hydraulic conductivity tests. Core samples will be taken from the packing to determine uniaxial compressive strength, splitting tensile strength, triaxial shear strength, Young's modulus, and Poisson's ratio. Tests will be designed after ASTM standards, and three repeat tests will be performed to establish the reproducibility of the test results. The results of these tests will be used to assess the structural integrity of the packing material.

Physical properties tests, using packing altered to simulate expected conditions at the start of resaturation (e.g., long-range exposure to heated, moist, methane-rich condition, gamma-irradiation, and the effects of any expected salinity resaturation), will be performed (Section 8.3.4.3.5).

8.3.4.4.5.3.2 Packing nondestructive examination study.

Nondestructive testing will be studied and equipment will be developed to evaluate the waste package packing materials to ensure that specified physical characteristics and quality requirements are achieved. Additional nondestructive examination will be developed to evaluate the structural integrity of packing materials.

Two nondestructive examination activity areas associated with the development of waste package packing technology will be studied. The first area is the fabrication of the packing material. The objective of this application of nondestructive examination is to ensure that variables, such as the density and the integrity of the material, meet specified requirements. The second area is the monitoring of preformed packing units during handling and waste package assembly. The effects of storage on the dimensions, properties, and integrity of the packing will be evaluated prior to assembly. These activity areas will result in development of nondestructive testing methods and equipment, final specifications, and examination procedures.

A list of tests to be performed, parameters to be evaluated, and data that will be generated is given in Table 8.3.4.4-14.

8.3.4.4.5.3.2.1 Nondestructive examination of fabricated packing. For preformed packing, additional inspections will be required after fabrication. Following the study and investigation of applicable nondestructive examination techniques, examinations will be conducted on fabricated packing. This initial examination is intended to examine and screen the preformed packing for voids and other conditions that would degrade physical properties. Following subsequent processing such as drying, baking, or sintering, the packing will be subjected to further nondestructive examinations that will locate flaws such as shrinkage, cracking, and porosity, as well as measure the density and other physical conditions that could degrade the required properties and performance of the packing. In both steps of this process, an information interchange will be maintained with the fabrication process development activities (see Section 8.3.4.4.5.3.1.1), to ensure that nondestructive examination findings are considered and used to further improve the reliability of the process and the uniformity of the material.

Experimental packing materials produced by initial fabrication process activities will be "graded" by nondestructive examination into various categories based on density, void content, porosity, cracking, and general uniformity. Physical tests intended to evaluate hydraulic conductivity will be correlated with nondestructive examination measurements. Information will contribute to the establishment of acceptance criteria for production testing.

Radiography, a volumetric examination, is expected to be one of the major nondestructive testing methods to be used. Radiographic developments will be directed to the implementation of filmless techniques combined with automated scanning and signal processing. Examination reliability will be a goal of this development. The results of the radiographic examination will be an assessment of the density of each area of the packing, as well as the detection of unacceptable flaws. Acceptable limits will be determined by structural analysis and by correlation with physical properties testing.

Acoustic/vibrational test methods will also be evaluated during this activity. Acoustic procedures require the packing to have sufficient hardness and stiffness to support the introduction and propagation of elastic waves. Acoustic procedures may be applicable for determining the overall elastic properties of the materials. This technique acquires and analyzes transient vibrational responses that allow the elastic-modulus and average density of the packing to be determined. These measurements will be valuable for checking the physical properties in a reliable, cost-effective manner.

Table 8.3.4.4-14. Summary of tests in packing nondestructive examination study

Test title	Abbreviated description of test method	Relevant parameters
X-ray examination	Measures integrity of transmitted x-rays passing through packing material	<ul style="list-style-type: none"> • Flaw characterization • Density variation
Acoustic/vibrational	Measures transient response of acoustic wave introduced by shock impulse	<ul style="list-style-type: none"> • Packing uniformity
Microwave	Measures reflected radiofrequency-energy as waves travel through material	<ul style="list-style-type: none"> • Packing uniformity
Fiber optic/closed-circuit television	Provides capability of visualizing surfaces in tight, inaccessible, or remote areas	<ul style="list-style-type: none"> • Surface flaws characterization
Air-coupled acoustic	Provides noncontacting method of measuring the uniformity and dimensions of surfaces	<ul style="list-style-type: none"> • External dimensions

PST87-2005-8.3.4-41

Visual and surface examination techniques also will be developed and used along with dimensional tests to ensure that the packing meets dimensional requirements. The accuracies of all nondestructive examinations will be investigated from plus or minus 2% to plus or minus 15% of the intended measurement.

Upon completion of the nondestructive examination fabrication process testing and associated feasibility tests, a prototype nondestructive testing system will be designed and fabricated. The nondestructive examination methodology will be used to evaluate prototype production of the packing materials. The objectives of building the prototype system will be to validate nondestructive examination tests in a prototype production environment, provide data on packing quality, and obtain data that will support and contribute to the finalization of the waste package design.

8.3.4.4.5.3.2.2 Nondestructive examination after packing handling. For preformed packing for the current reference waste package design, non-destructive examination handling examinations and tests will take place before and after placement of the packing materials in the emplacement shell. Initial testing will be directed toward measurements that will ensure that the packing material meets specifications in the following areas:

- Retention of the original properties and integrity through storage and handling.
- Proper installation in the waste package system.

Nondestructive examination developed for fabrication may be applicable to this phase of the study. In addition, examinations will have to be developed to evaluate the integrity of packing following installation. The following are two areas of concern:

- During assembly, no damage to the packing has occurred that would interfere with its functions.
- After emplacement and loading the waste container, no damage has been introduced.

If processing and subsequent storage results in significant changes in preformed packing moisture content, dimensions, or density, other examination and testing approaches will need to be considered. For example, if excessive shrinkage has occurred, it would be necessary to make dimensional and configuration (shape) validation tests to ensure that subsequent procedures, such as installation in the emplacement shell and matching with adjacent packing, can be performed properly. Uniformity of packing segments is a requirement since hydraulic conductivity will depend on the swelling capacity of barrier materials. To address these examination areas, alternative methods of testing will be studied. One of the primary tests of installed packing would utilize visual methods incorporating remotely controlled television cameras, fiber optics, and air-coupled acoustic techniques. The acoustic

technique has been applied to automotive assembly plants to evaluate complex assemblies for proper assembly, detect missing parts, and guide robots. The use of microwaves will be also be considered, particularly if loose material is used in place of the reference design preformed packing materials.

8.3.4.4.5.3.3 Packing handling and emplacement study.

This study is directed by the current reference waste package design, which includes preformed packing. The objectives of this study are (1) to test the structural integrity of preformed packing and its resistance to damage from handling after fabrication and during insertion into the emplacement shell; (2) to evaluate the packing for resistance to damage from handling the shell with the packing contained within; and (3) to evaluate the packing for resistance to damage from insertion of the container into the waste package. Additional tests may be developed to address alternate packing emplacement methods.

Results from initial packing materials testing indicate that the preformed basalt/bentonite material appears to have adequate strength to support the heaviest anticipated waste container. However, in the reference conceptual design, the packing must be handled after fabrication, transported to and within the emplacement shell, and subjected to waste container insertion. Hence, to make the preformed packing concept viable, the packing must not only support the normal loading of the waste container, but must also withstand concentrated loads that result from handling and container emplacement.

The data from this study will provide information for the waste package design activities. The data also will be applied to repository design tasks for packing handling and emplacement equipment design. Because of the unique nature of the tests to be performed, specific technical procedures will need to be developed. Tests to be described in more detail in the following sections are summarized in Table 8.3.4.4-15. Also included are parameters to be evaluated and the data to be produced from each test.

Table 8.3.4.4-15. Summary of tests in packing handling and emplacement study

Test title	Abbreviated description of test method	Relevant parameters
Packing structural integrity handling tests	Subject individual packing elements to handling and shell emplacement loading to determine resistance to damage	<ul style="list-style-type: none"> • Handling induced strain (handling load and shock limits)
Packing/emplacement shell handling tests	Subject a shell that is loaded with packing elements to normal handling loads to determine packing and shell resistance to damage	<ul style="list-style-type: none"> • Handling induced strain (handling load and shock limits)
Packing/container emplacement tests	Load simulated container into a packing--prepared waste package to determine effect on packing. May also evaluate "slipper" as aid to container insertion	<ul style="list-style-type: none"> • Packing strength and wear/abrasion resistance • Handling clearances

PST87-2005-8.3.4-42

8.3.4.4.5.3.3.1 Packing structural integrity handling tests. Three sets of tests for each packing configuration will be conducted to determine how easily and safely the individual preformed packing units (i.e., ring, end plug, and shield plug) can be handled without damage. The packing will be handled with specially designed lifting and orienting devices while being monitored for gravity-loading with accelerometers and for strain with embedded strain gages. Damage in the form of cracks, both visual and hidden, and localized damage, such as spalling or permanent alteration due to concentrated loading, will be monitored both by observation and nondestructive examination methods. The packing ring and end plugs also will be monitored to determine how vulnerable the surfaces and joint might be to handling and impact loading. Also of interest will be how prone the packing units will be to sliding (abrasive) damage as they are emplaced in the shell. If the surfaces are undesirably friable, vertical assembly may be needed to reduce the load.

Parameters evaluated as part of this test include gravity loading, to determine whether the units will disintegrate under their own weight, strain due to applied handling loads, and abrasion resistance. The data produced will help determine the gravity-loading and stress limits for the individual packing elements and will help provide overall guidelines for handling the packing elements. The data will also be provided to repository design tasks for packing handling equipment design.

8.3.4.4.5.3.3.2 Packing/emplacement shell handling tests. These tests will help determine how resistant to damage the packing might be as it is transported and emplaced within the repository borehole. A shell will be fabricated and the packing rings and end plugs inserted as a continuation of the packing structural integrity tests. The shell/packing assembly will be maneuvered through various orientations while the shell and packing are monitored for strain and gravity-loading. After the shell has been handled through all the motions that it would see in the repository, the packing will be inspected for damage using nondestructive examination techniques. The packing will also be carefully removed and visually examined. Independently, the shield plug will be tested by emplacing it into the physical test model described in Section 8.3.4.4.5.3.3.3.

Parameters evaluated as part of the packing/emplacement shell handling tests include gravity loading, strain, abrasion resistance, and non-destructive examination methods. The data produced will help determine the gravity-loading and stress limits for the packing/shell assembly and will help provide overall guidelines for handling the packing/shell assembly. The data also will be supplied to repository design tasks for packing/emplacement shell handling equipment design and procedures development.

8.3.4.4.5.3.3.3 Packing/container emplacement tests. These tests will determine how resistant to damage the packing rings will be to container emplacement. A full-scale, physical test model of the borehole and waste package will be fabricated for testing. The top half of the physical test model will be removable to facilitate access to the packing. The fully weighted container with different shaped nose pieces will be slid into place three times for data repeatability to see what effect the sliding motion will have on the packing.

An additional three series of tests will also be performed with a "slipper" in place on the packing valley to slide the container on and to distribute the emplacement loads. The slipper will be a sheet-metal plate formed to match the packing inside diameter and inserted into the packing before container insertion. Removal of the slipper after container emplacement will be evaluated. Slipper removal may be difficult to accomplish and may tend to damage the packing as it is extracted from beneath the container while bearing heavily on the packing from the weight of the container.

This test will also make possible the evaluation of other container emplacement options such as cantilevering the container into position to reduce sliding on the packing and using other insertion aids.

Parameters evaluated from this test include gravity loading, strain in both the packing elements and the shell, and nondestructive examination methods. These parameters will define the packing's resistance to container sliding, packing breakage during container emplacement, and performance of a slipper. In addition, performance of nondestructive evaluation methods of the waste package assembly will be evaluated.

The waste package trade and engineering study activity (Section 8.3.4.4.3.3.1) and configuration design activity (Section 8.3.4.4.3.3.2) may result in a recommendation to use in-room emplacement of the waste package. If this occurs, different methods for fabricating, handling, emplacing, and nondestructively examining packing will need to be developed. Filled and tamped packing and pneumatically transferred packing are emplacement methods that have already been given preliminary assessment. These methods may be used instead of, or in combination with, fabrication and emplacement of preformed units. The preliminary tests will supplement additional testing to refine and assess the methods and procedures. Important parameters to be measured are average emplaced density and density variations, basalt and bentonite spatial distribution and uniformity, process throughout, and emplacement machine development needs. If the short horizontal borehole emplacement configuration is retained, it may be necessary to use packing pneumatic transfer to improve the emplaced packing density. This will require supplemental development testing.

8.3.4.4.5.4 Application of results

This waste package packing development investigation will provide the waste package configuration design-related activities in Section 8.3.4.4.3 with specific packing materials, components, and processes data. The results are based on large-scale or full-scale tests that apply expected repository operating conditions to selected packing materials and design configurations. These tests will develop and evaluate waste package fabrication, assembly, emplacement, and nondestructive evaluation processes for prototype packing.

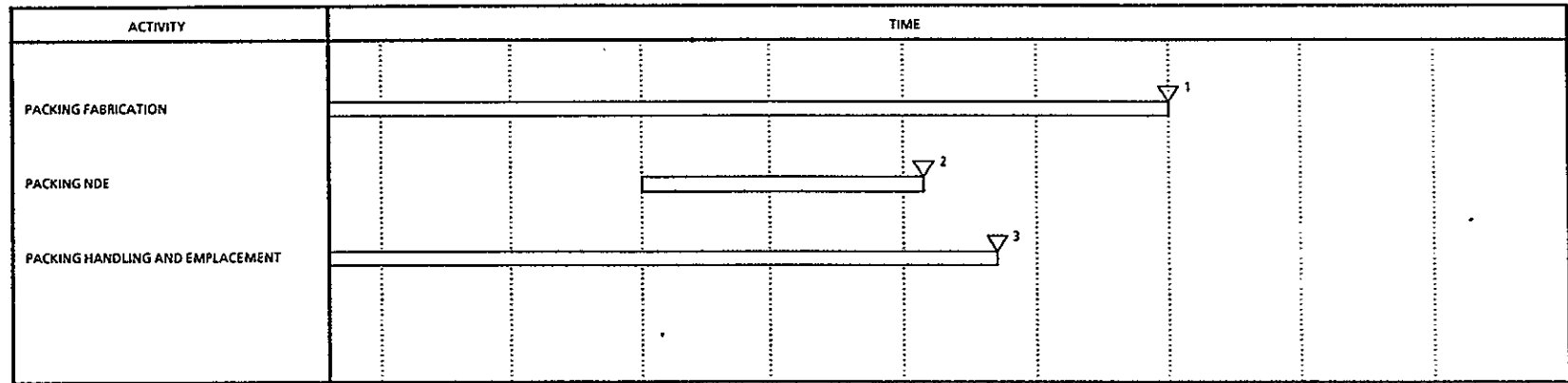
The experimental data are to be used as input to various design activities and testing and will be used to prepare specifications for the final waste package packing components and processes. The following summarizes the application of the physical properties data:

- Swelling pressure data will enable the waste package designer to specify the composition of packing materials and the density that exhibits a swelling pressure that does not exceed hydrostatic pressure. These data, along with the potential for reduced swelling capacity due to dehydration or steam reactions, are needed as input to mass transport models that will be used to evaluate radionuclide release.
- For design purposes, hydraulic conductivity and shear strength data will be used to refine the required basalt to bentonite ratio for the reference packing material such that satisfactory low permeability and sufficient bearing strength characterize the packing material.
- For design purposes, thermal conductivity data will be used to specify the packing materials composition and density that are characterized by adequate thermal conductivity to prevent unacceptably high-peak temperature.
- For design purposes, strength data (i.e., tensile, compressive, and shear) will be used to specify composition and density of the preformed packing materials such that the packing is durable enough to withstand the manufacturing activities, storage, transportation, and installation with no significant degradation of expected performance.

8.3.4.4.5.5 Schedule and milestones

Waste package packing development investigation studies will produce packing material physical properties test data, procedures, and material specifications. Deliverable products will be periodic documents that report packing material test data. The test data information will be used in the final report for repository licensing support of the waste package design.

The packing development investigation schedule is shown in Figure 8.3.4.4-5. Detailed control schedules will be prepared for each study for each fiscal year. The schedule will show major equipment required, planned activities, and milestones.



PS&S-2014-0.3.4.10

- ▽ 1 ISSUE PACKING MATERIAL SPECIFICATIONS (SUPPORT 90% LAD).
- ▽ 2 ISSUE PACKING NDE PROCEDURES AND SPECIFICATIONS (SUPPORT 30% LAD)
- ▽ 3 ISSUE PACKING HANDLING AND EMPLACEMENT PROCEDURES AND SPECIFICATIONS (SUPPORT 30% LAD)

LAD = LICENSE APPLICATION DESIGN
NDE = NONDESTRUCTIVE EXAMINATION

Figure 8.3.4.4-5. Packing development investigation.

8.3.4.4.6 Qualification testing investigation

Waste package qualification testing will be conducted as part of the waste package design development program. This investigation will provide data needed to meet explicit requirements of the regulations contained in 10 CFR 60, Parts 113, 135, and 140 (NRC, 1987a). Reasonable assurance of substantially complete containment by the waste package and gradual radio-nuclide release from the engineered barriers system will be demonstrated on the basis of predictive performance models. Information obtained from the qualification testing investigation will be used to confirm results from small-scale laboratory tests and to validate predictive codes. Qualification testing is necessary to validate the results of performance models that will be used to assess probable waste package performance in the repository.

8.3.4.4.6.1 Purpose and objectives

The purpose of qualification testing of large-scale (approximately half-scale up to full-scale) waste packages in a simulated repository environment is to provide information needed to verify results from laboratory (e.g., coupon size) tests and to validate predictive performance assessment codes.

8.3.4.4.6.1.1 Information description.

Information will be obtained from the following studies:

- Container corrosion qualification testing.
- Packing saturation qualification testing.
- Container settlement testing.
- Waste package in situ testing.

Container corrosion qualification testing will provide information on the nature and extent of container corrosion under simulated repository conditions using a large-scale test vessel (autoclave) that simulates an emplaced waste package in the repository. The test will measure the corrosion rate of candidate container materials under conditions that are expected to occur after the packing material has been saturated and waterflow equilibrium has been established.

Packing saturation qualification testing is a large-scale test conducted in a large test vessel (autoclave) that simulates an emplaced waste package surrounded by groundwater in the repository after closure. The packing material will begin the test dry, and the subsequent packing saturation behavior will be monitored. Prototypic packing used in the test will be altered to simulate the expected condition of packing at the time of resaturation.

Container settlement testing is a large-scale test to determine if movement of the waste container within the packing envelope is likely to occur as a result of packing mobility under anticipated repository conditions. If a given packing formulation exhibits excessive viscoelastic/plastic behavior during the test, the basalt-to-bentonite ratio will be refined and the packing retested.

Waste package in situ testing will measure actual container corrosion and packing performance in the repository under at least preclosure heat, thermal gradients, moisture gradients, and rock dry-out conditions. It may not be feasible to duplicate full postclosure conditions equivalent to the container corrosion qualification test in the in situ test. This test will occur after the license application design and after specific test details have been developed.

Data from the large-scale container corrosion and packing saturation tests will be used in modeling activities that will affect the license application design of the waste package. The half-scale tests will be conducted on waste package configurations consistent with the advanced conceptual design. The license application design waste package will establish the full-scale container corrosion and packing saturation test designs. Data from the full-scale tests will be used for performance confirmation analyses and to validate, in part, waste package performance codes. Data from the container settlement test will be used to verify or refine the packing design with respect to viscoelastic behavior.

8.3.4.4.6.2 Rationale

The qualification testing investigation is designed to provide information to address needs identified to resolve, in part, performance and design Issues 1.4 and 1.10.

The information needs to resolve the issues will require test data to predict the following:

- Saturation behavior of the packing.
- Corrosion behavior of the container material.
- Settlement of the emplaced waste container.

In addition to accurate corrosion data, information on the rate of packing saturation and container/packing interaction under simulated repository conditions is required. The relevant information needs addressed, in part, by the qualification testing investigation are given in Table 8.3.4.4-16, along with the technical concerns and relevant strategies that direct studies performed as part of this investigation.

8.3.4.4.6.2.1 Issue resolution strategy.

Information obtained from the studies conducted as part of the qualification testing investigation will be used to support information needs to predict waste container lifetime. The information needs will be used to support the strategies developed to resolve the issues identified in Section 8.2.2. A summary of the strategies related to this investigation is included in Table 8.3.4.4-16.

Table 8.3.4.4-16. Information needs to be satisfied by the qualification testing investigation

Information need		Synopsis of relevant strategy for technical concern	Relevant technical concern (see Sections 7.5 and 8.2.2)
Title	Abbreviated description		
General corrosion Localized corrosion	Container provides sufficient corrosion resistance	<p>Apply time-phased container failure distribution predictions to calculate the release of radionuclides to the accessible environment. Use qualification testing results to validate, in part, predictive models.</p> <p>Validate empirical and mechanistic-based predictive models on the basis of large-scale qualification tests.</p>	<p>Issues 1.4 and 1.5</p> <p>Technical concerns: No. 8 - Predicting long-term corrosion performance using short-term data No. 11 - Container failure rate and its effect on radionuclide release</p>
Physical properties and processes of packing materials	<p>Groundwater flow rate through packing:</p> <ul style="list-style-type: none"> Time to resaturation <p>Resist plastic deformation:</p> <ul style="list-style-type: none"> Container settlement 	<p>Conduct qualification tests to measure the time to resaturation under expected pressure and temperature conditions. Integrate model predictions with the experimental results to estimate the time required for complete saturation of the packing. Use post-test examinations to determine effects of steam on packing physical properties.</p> <p>Measure container settlement using large-scale tests simulating the expected temperature, pressure, and loading conditions. If necessary, alter packing composition until settlement is within accepted limits.</p>	<p>Issues 1.4 and 1.5</p> <p>Technical concerns: No. 4 - Time of packing resaturation No. 12 - Extrapolation of long-term packing performance on the basis of short-term test data No. 13 - Effects of steam on packing physical properties</p> <p>Issues 1.4 and 1.5</p> <p>Technical concern: No. 14 - Ability of packing to maintain waste package configuration</p>

PST87-2005-8.3.4.50

8.3.4.4.6.2.2 Constraints.

A reasonable expectation that the waste package performance objective will be met must be demonstrated. Because the waste container has a design life of greater than 1,000 yr, this performance can only be demonstrated by predictive performance assessment models. Qualification testing of the waste package under simulated repository conditions will provide information needed to help validate the performance assessment code predictions and verify container materials and engineering design choices. Instrumentation and testing methodology developed to perform the qualification tests may also be applied to in situ performance confirmation tests. The in situ performance confirmation tests are required to demonstrate, to the extent feasible, that during the operating period the repository conditions and waste package behavior will be as predicted.

An investigation methodology diagram is shown in Figure 8.3.4.4-6 to indicate the interrelationship of the studies within the investigation and the logic necessary to support meeting the waste package performance goals.

8.3.4.4.6.3 Description of studies

The qualification testing investigation comprises the following four studies:

1. Container corrosion qualification testing.
2. Packing saturation qualification testing.
3. Container settlement testing.
4. Waste package in situ testing.

This section provides a summary description of each study, the test methods that will be used, and the analyses that the study results will support. Detailed descriptions of each study are provided in study plans that support this document.

8.3.4.4.6.3.1 Container corrosion qualification testing study.

The objective of container corrosion qualification testing is to measure the corrosion rate of candidate waste package container materials in half-scale and full-scale configurations that simulate the repository environment after water saturation of the packing has occurred, and the groundwater flow rate has equilibrated. Large-scale testing is necessary to confirm laboratory results and to identify effects that cannot be adequately simulated in small-scale tests. Such effects could include the establishment of galvanic cells due to variations in the chemical environment surrounding an emplaced waste container. One half-scale design will be based on the reference waste package advanced conceptual design. An additional half-scale and a full-scale test

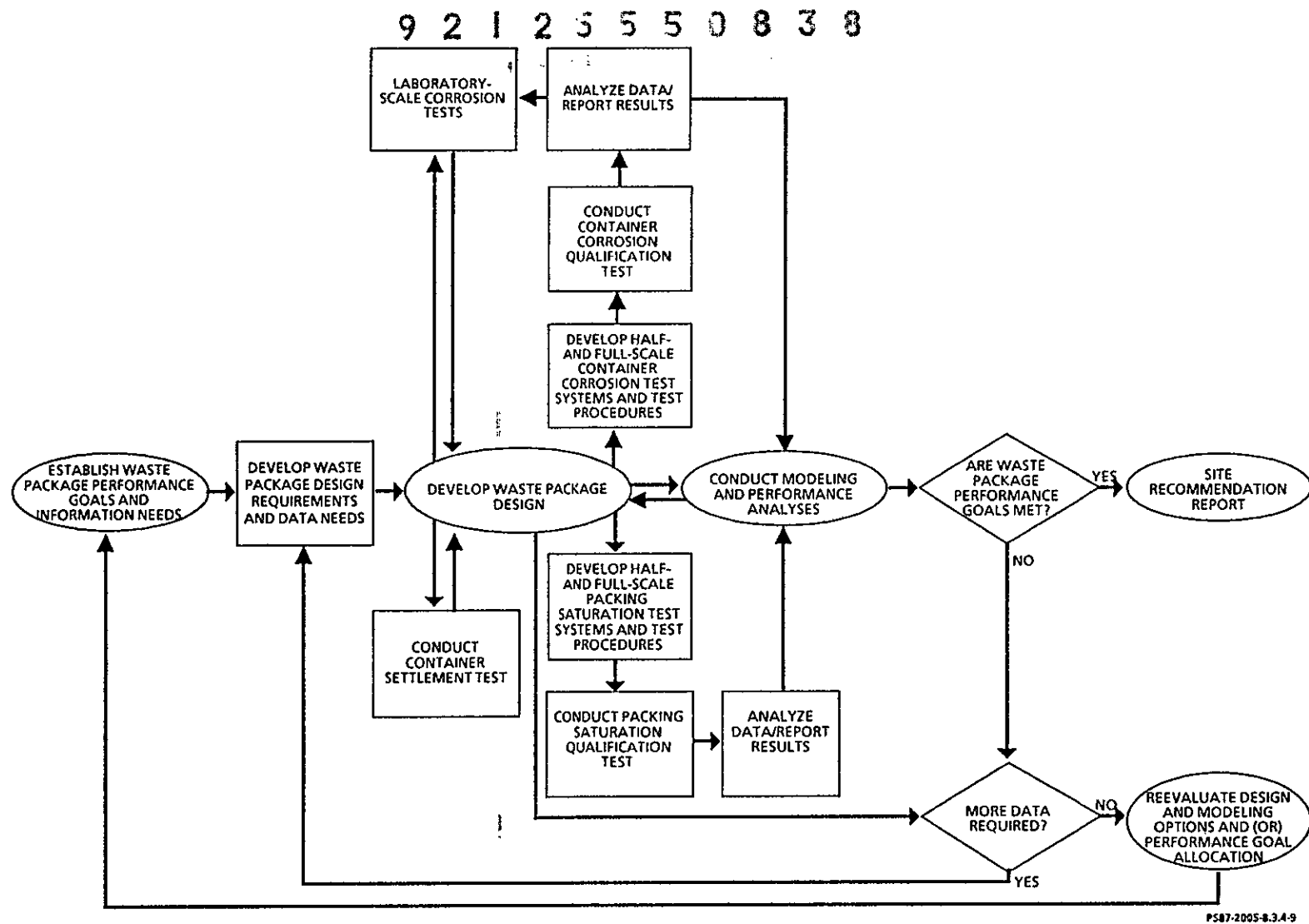


Figure 8.3.4.4-6. Qualification testing investigation methodology diagram.

9 2 1 2 5 5 0 8 3 9

configuration will be based on the license application design. Testing will be conducted in a specially designed pressure vessel using a waste package model that includes packing material and an internally electrically heated container. External trace heating is also used to maintain the required temperature gradients required for accurate simulation. Tests of 1 yr or longer will be conducted using the half-scale configuration to provide data to support validation of predictive corrosion performance models. Corrosion rate data will be obtained from on-line sensors and total (cumulative) corrosion data determined by post-test examinations. Multiyear testing of full-scale configurations is primarily intended to provide long-term confirmation data after the license application design has been submitted. Analysis of the data will be made to relate the results to data from laboratory-scale (coupon) corrosion tests. Data from container corrosion qualification testing are needed to support the development and validation of corrosion models for candidate waste container materials. Corrosion models will be used as a guide to container design and to predict the containment performance of the waste package.

The objectives, test methods, and analysis of results from container corrosion qualification testing are discussed in the following sections.

8.3.4.4.6.3.1.1 Test methods. The container corrosion study is meant to simulate the repository environment in the postclosure period after the packing has been saturated and the waste package temperature and groundwater flow have reached equilibrium (steady-state) levels. Testing will be conducted at the hydrostatic pressure of the repository horizon (9.4 MPa (1,363 lbf/in²)) in the expected long-term chemically reducing environment. Test temperatures of 100 °C for iron-based materials and 200 °C for copper-based materials have been chosen since laboratory tests indicate these are the temperatures at which peak corrosion rates are expected for each material type.

A 1-yr and a multiyear test will be conducted on half-scale waste package models at the conditions described above. The half-scale waste package will consist of an electrically heated waste container model, packing material, and a thin-wall outer emplacement shell. The packing will be designed to permit rapid flooding of the test vessel at the beginning of each test. After the autoclave has been filled with simulated groundwater (which has been equilibrated with basalt and saturated with methane at 9.4 MPa (1,363 lbf/in²)), additional groundwater will be pumped through the autoclave at a rate of between 5 and 50 L/yr or 1 and 10 μ L/min. The waste container model will be designed as a pressure vessel to withstand the external pressure in the autoclave and will be internally and externally heated to produce the required operating temperatures and gradient.

The amount of container corrosion will be monitored as a function of time during the test by sensors, which will be developed as part of the study. At the conclusion of each test, the waste package model will be removed from the autoclave and disassembled for posttest examination. The thickness of the corrosion product layers and assimilated packing will be determined, and the material will be collected and analyzed for structure and composition. The homogeneity and integrity of the saturated packing material used in the test will also be evaluated. The test methods used and the relevant parameters evaluated are summarized in Table 8.3.4.4-17. A detailed description of the study is given in the Container Corrosion Qualification Testing Study Plan (Bain, 1987).

Test procedures that will be used include the following:

- Test article assembly.
- Controlled welding.
- Material control.
- Test system loading and unloading.
- Data control.
- Instrument calibration.
- Test system operation.
- Data reduction.
- Groundwater sampling and analysis.
- Corrosion film sampling, measurement, and analysis.
- Metallurgical examination.
- Surface analysis.

Many of the procedures will have to be developed prior to testing. The need for additional procedures also may be identified as the test develops.

Table 8.3.4.4-17. Summary of tests in container corrosion qualification study

Test title	Abbreviated description of test method	Relevant performance parameters
Container corrosion qualification test	Measure corrosion of container materials under simulated repository conditions and during post-test examinations	<ul style="list-style-type: none"> • Uniform corrosion penetration • Localized corrosion penetration

PST87-2005-8.3.4-45

8.3.4.4.6.3.1.2 Analysis of results. The total amount of container corrosion will be determined at the end of the test by physically examining the model container at various locations, such as welds, heat-affected zones, and simulated surface defects. The total measured corrosion will be used to determine an average corrosion rate for various locations on the container. Data from the on-line sensors will be analyzed to determine the global corrosion rate as a function of time. The corrosion rate as a function of time will be correlated with results from the smaller scale laboratory corrosion tests and from total corrosion measurements to provide input to corrosion models used for waste container design. Metallurgical and container surface examination results will be analyzed for evidence of localized corrosion; any nonuniform corrosion rates will be determined, and the need to, modify container corrosion models will be assessed.

Changes in the groundwater chemistry will be analyzed in terms of reactions that occur in laboratory test systems. These results and data obtained from surface film analyses will be used to supplement other information on the corrosion mechanisms to support the corrosion model with valid mechanistic interpretations. Data from the corrosion film analyses also will be used to improve the modeling of the transport of chemical species through the corrosion layers for use in release-rate evaluations.

8.3.4.4.6.3.2 Packing saturation qualification testing study.

The purpose of the packing saturation qualification test is to measure the rate of groundwater movement through the initially dry packing material under conditions that closely simulate those expected in the repository during the unsaturated postclosure period. The objective of the test is to verify waste package design decisions and to aid in the validation of computer models that predict waste package thermal-hydraulic conditions. Release-rate predictions needed to assess compliance with the NRC regulations will require reliable information on groundwater travel through the packing material and packing thermal-hydraulic behavior.

The objectives, test methods, and analysis of results from packing saturation qualification testing are discussed in the following sections.

8.3.4.4.6.3.2.1 Test methods. Approximately half- and full-scale test systems will be used to simulate the waste package in the repository during the early postclosure period. As with the container corrosion tests, half-scale packing saturation qualification test results will support predictive model validation, while full-scale testing is intended primarily to produce long-term confirmation data. The test will begin with the dry packing, and the packing saturation rate will then be measured under the conditions of a slowly moving steam/water front and chemically oxidizing/reducing environment. Packing material used in the test will simulate the condition of prototypic material that has been altered by exposure at service temperature to a steam/methane atmosphere for up to 250 yr. Simulated groundwater will also be altered to reflect the conditions expected at the time resaturation begins.

Techniques to continuously monitor the rate of water penetration through the packing in these scaled tests will be developed as part of the overall test program. Potential methods include pulsed thermocouple or neutron backscatter measurements to measure the location of the water front as the packing becomes saturated. Accuracy levels of the potential techniques will be determined as the methods are developed. Accuracies needed to support the codes will be established by appropriate performance sensitivity analyses.

Tests will be conducted at a constant waste container/packing interface temperature of 300 °C with two constant 10 °C temperature gradients in the radial and axial container directions. Due to uncertainties in the expected time for saturation, groundwater flow rate to the model waste package has not been established. Initial rates will simulate the expected conditions in the repository, typically expected to be in the range of 5 to 50 L/yr or 10 to 100 μ L/min. A variable pressure in the test vessel will be maintained from 0.1 to 3.0 MPa (14.5 to 435 lbf/in²). Although the test design permits inclusion of a radiation field, a radiation source will not be included in the initial tests. This is done to permit more precise monitoring of the test system during the initial phases of the test.

Test temperature will be maintained by heaters inside the model container and external trace heaters. The planned test will be established by controlling the amount of methane dissolved in the groundwater. The methane will be introduced during pretreatment prior to the groundwater entering the test vessel to simulate the early postclosure condition near the waste package. The chemical redox state of the test system will be established by the interaction of the incoming groundwater with the waste package within the autoclave. The initial chemistry of the groundwater will be accurately controlled to the Grande Ronde 4 composition, reacted with basalt in a pretreatment vessel, and introduced into the autoclave. The chemical composition of the groundwater in the autoclave will be set by reactions within the autoclave, the rate of corrosion of the model waste container, and the alteration products formed in the packing material and the corrosion layers.

Data obtained during the packing saturation test will include temperature, pressure, and water content at various locations in the packing as a function of test time. Posttest examinations and testing will provide supplementary packing data such as the following:

- Shear strength.
- Swelling pressure.
- Saturated density.
- Permeability.
- Thermal conductivity.

A posttest examination of the model container will be conducted to assess the extent and nature of any corrosion that occurred during the test. The test method and relevant parameters evaluated are summarized in Table 8.3.4.4-18. A detailed description of the study is given in the packing saturation qualification test study plan.

Table 8.3.4.4-18. Summary of tests in packing saturation qualification study

Test title	Abbreviated description of test method	Relevant parameters
Packing saturation qualification test	Measure the saturation rate of initially dry packing in a simulated repository post-closure environment and perform post-test examinations	<ul style="list-style-type: none"> • Creep rate • Shear strength • Hydraulic conductivity

PST87-2005-8.3.4-46

8.3.4.4.6.3.2.2 Analysis of results. Spatial profiles of moisture content through the packing will be measured as a function of time, temperature, and hydrostatic pressure. The results of the tests will be correlated with results from laboratory-scale packing tests. Results from the packing saturation qualification test will be used to validate codes that predict water transport through the packing and thermal hydraulic behavior.

8.3.4.4.6.3.3 Container settlement testing study.

The objective of the container settlement testing study is to determine whether the prototypic packing design will have sufficient bearing capacity (strength) to limit settling of the waste container after packing saturation has occurred. Sufficient bearing capacity is required for the following reasons:

- o To maintain required packing thickness under the waste container.
- o To prevent the occurrence of void spaces in the packing after saturation due to nonuniform swelling and (or) settlement.

The bearing capacity or strength of the packing varies with the effective or intergranular pressure (stress), bulk density, particle interlocking, cohesion, moisture content, method of compaction, particle-size distribution, and ratio of basalt and bentonite components in the mixture. Container settlement is a function of the packing material properties and the geometry and weight of the packing and waste container. Testing will provide bearing capacity and settlement data to determine adequate packing material composition and density and to confirm that container settling due to visco-elastic deformation of saturated packing does not occur in engineering-scale test systems.

Both laboratory- and engineering-scale testing will be conducted on prototypic waste package packing suitably altered to reflect the condition of the packing at the time in the repository history represented by the test. The laboratory tests will consist of consolidation and shear-strength tests on small sections of packing material. The larger engineering-scale testing will be conducted with a scaled model of the waste package. Packing in the model package will be saturated under controlled environmental conditions, and any settlement of the container within the waste package will be measured. Testing times will be extended to allow measurement of any secondary (long-term) consolidation of the packing material that may occur after any initial (short-term) consolidation.

8.3.4.4.6.3.3.1 Test methods. Laboratory testing of the packing will measure settlement (consolidation of the packing) and shear strength. Test samples will consist of a mixture of bentonite and crushed basalt compacted to specified densities by the reference and alternate fabrication techniques. The samples will be tested dry, partially saturated, and saturated to evaluate the sensitivity of the strength properties to varying degrees of moisture content, since all three conditions will occur at some time during the design life of the repository.

The settlement tests will be conducted in a load frame triaxial cell or in a consolidometer. During the test, maximum compression strains will be measured as a function of applied load, up to the load that the packing will be subjected to, in the emplaced waste package. Shear-strength tests will be conducted in a load frame triaxial cell. During the shear strength test, an axial load will be applied to a confined or unconfined sample at constant load or strain. The load or strain will be increased incrementally until the sample fails by a shear mechanism. Independent variables considered as part of the settlement and shear-strength tests include the following:

- Temperature (approximately 60 to 250 °C).
- Bulk packing density (1.5 to 2.1 g/cm³).
- Clay/basalt ratio (15:85 to 50:50).
- Confining pressure (0.1 to 3.0 MPa (14.5 to 435 lbf/in²)).
- Pore pressure (0 to 10 MPa (0 to 1,450 lbf/in²)).
- Moisture content (dry to saturated).
- Packing compaction method.

The wide range in the clay/basalt ratio is related to simulating the packing properties at long times as part of manipulating the independent test variables to simulate the expected repository environments, including the potential for conversion of some of the basalt to clay. Dependent test variables to be measured experimentally are load and strain rate for the settlement tests and load, strain, pore pressure, peak strengths, and residual strengths in the shear tests.

Laboratory procedures will be designed to follow standards such as ASTM D 2850-82 and D 4186-82 as closely as possible. At least three repeat tests should be performed for each set of test conditions. Settlement testing will continue over a 1-yr period to investigate the effects of long-term secondary consolidation on the packing material properties.

Container settlement tests also will be conducted on an engineering-scale waste package model within an autoclave test system. The waste package model will be designed to have a full-scale cross section and full container weight-per-unit length. The model length will be long enough to minimize end support effects. The autoclave test system will have a cylindrical geometry that approximates the waste package in an emplacement borehole. Packing material will fill the volume between the simulated waste container and the emplacement shell. The test will begin with saturated packing under low flow rate conditions expected in the repository environment. Electrical resistance heaters within the waste package model and external trace heaters will

simulate waste heat generation inside the waste container.

Independent tests at a pressure of 9.4 MPa (1,363 lbf/in²) will be conducted at 100 and 200 °C for about 1 yr each. The model waste container will be monitored continuously for downward movement (settlement), and the pressure exerted on the container wall by the expanding packing will be measured. Following each test, core samples of the packing material will be obtained for additional physical property measurements such as hydraulic conductivity and strength. Synthetic groundwater and packing material samples will also be analyzed to determine the amount and composition of any alteration products. A summary of the tests that will be conducted as part of the container settlement test, the parameters to be evaluated, and the data to be produced are given in Table 8.3.4.4-19.

8.3.4.4.6.3.3 Waste package in situ testing study.

In situ testing of waste packages for design confirmation is a long-term part of the qualification testing investigation that will most likely occur during the repository construction and operating periods. Aspects of the waste package design that affect the site (e.g., heat and stress due to the thermal output) are addressed in the Section 8.3.2.2.3.4.3, which describes the in situ heater test that will be conducted as part of the exploratory shaft program. Specific plans for determining the in situ performance of the waste package with respect to container corrosion, packing saturation, and possible packing settlement have yet to be developed. Testing methodology and instrumentation requirements will be established and will be adapted from the

Table 8.3.4.4-19. Summary of tests in container settlement test

Test title	Abbreviated description of test method	Relevant parameters
Laboratory settlement test	Measure settlement rate as a function of load	<ul style="list-style-type: none"> • Shear strength • Consolidation • Creep rate
Laboratory shear strength test	An axial load is applied to a confined or unconfined sample in a triaxial mode at constant load or strain until failure	<ul style="list-style-type: none"> • Shear strength • Creep rate
Engineering-scale tests	Saturated packing is subjected to simulated repository environmental conditions to measure settlement of a model full-scale diameter waste package	<ul style="list-style-type: none"> • Shear strength • Creep rate

PST87-2005-8.3.4-47

other tests carried out as part of the qualification testing investigation. Testing of waste package performance may be conducted nondestructively in the repository with a limited number of destructive tests scheduled to verify nondestructive test results.

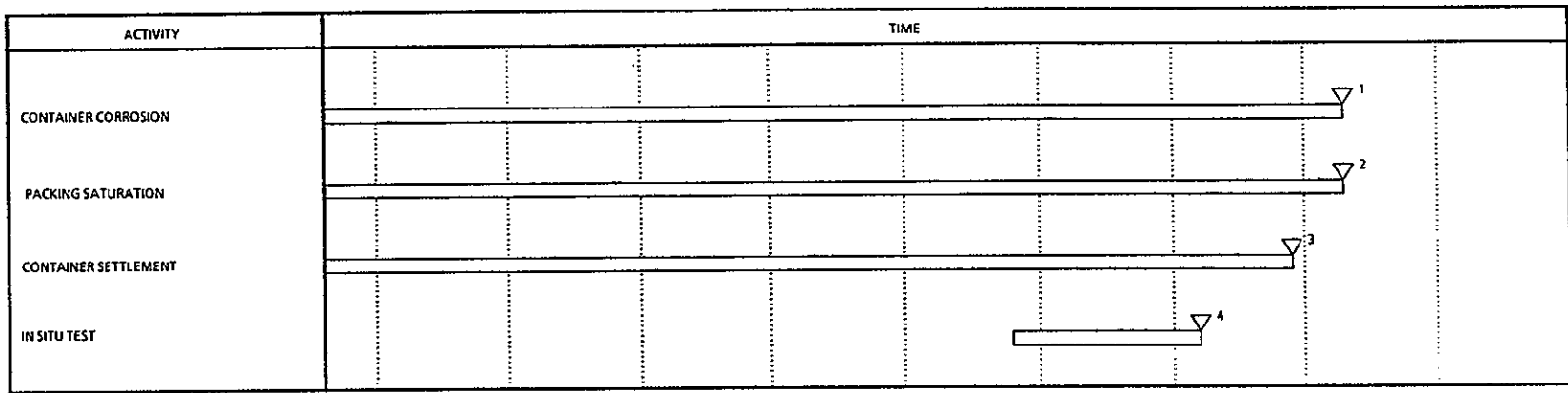
In situ tests involving radioactive materials in the package are not currently envisioned, but high-energy gamma sources could be employed to simulate the radiolytic effects expected in the repository during the period before container failure. None of the in situ test concepts currently being discussed would adversely affect the ability of the natural barriers to isolate waste.

8.3.4.4.6.4 Application of results

Specific performance assessment studies that will use the information produced by the qualification testing investigation are discussed in Section 8.3.4.5, which describes the waste package modeling program. Container corrosion and packing saturation test results will be used for waste package performance model validation. Results from the container settlement tests will be used to verify viscoelastic packing performance models and optimize the waste package packing composition and dimensions.

8.3.4.4.6.5 Schedule and milestones.

The schedule and milestones for the four studies in the qualification testing investigation are given in Figure 8.3.4.4-7.



PS&B 2014 R 3.4-11

- ▽ 1 CORROSION DATA FROM HALF-SCALE TESTS TO VALIDATE WASTE PACKAGE PERFORMANCE AND RELIABILITY ANALYSIS.
- ▽ 2 PACKING SATURATION DATA FROM HALF-SCALE TESTS TO VALIDATE WASTE PACKAGE PERFORMANCE AND RELIABILITY ANALYSIS.
- ▽ 3 CONTAINER SETTLEMENT DATA FROM FULL-SCALE TESTS TO VALIDATE WASTE PACKAGE PERFORMANCE AND RELIABILITY ANALYSIS.
- ▽ 4 PROVIDE IN SITU TEST PLAN TO LICENSE APPLICATION DESIGN FINAL REPORT.

Figure 8.3.4.4-7. Qualification testing investigation.

This page intentionally left blank.

9 2 1 2 5 5 5 0 8 4 8

8.3.4.5 Specific program for waste package modeling

The design of the waste package will be supported by analytical investigations performed by the design contractor and, independently, by the BWIP. Four investigations compose the waste package modeling program, which describes waste packages by mathematical and computational models and uses these models to analyze the physicochemical phenomena that take place in and around the waste package.

Container failure, radionuclide dissolution, and radionuclide transport are of primary interest when studying waste package design. Because there are a number of specialized physicochemical phenomena that contribute to container failure, radionuclide dissolution, and radionuclide transport, each phenomenon warrants separate discussion in the descriptions of specific investigations in which they are applied. These discussions compose the bulk of discussion on waste package modeling.

Background

A substantial amount of waste package analysis has been performed in conjunction with the SCP conceptual design. This analytical work is summarized in Section 7.4.6.

Summary of program

The waste package modeling program consists of analytical investigations required to support waste package design, including an investigation required to verify and validate computer codes and models used in the other investigations. While the relationship among the investigations and an explanation of the organization and aims of the analyses the investigations comprise are discussed in Section 8.3.4.5, the actual computer codes used in the analyses are discussed in Section 8.3.5.

The waste package modeling program is divided into four investigations. Section 8.3.4.5.3, performance sensitivity investigation, is a preparatory investigation intended to guide the design and testing programs and to refine the performance allocation presented in the issue resolution strategies related to the waste package. Section 8.3.4.5.4, performance and reliability investigation, comprises the analyses that predict the postclosure performance of proposed waste package design configurations. Section 8.3.4.5.5, impact stress and fracture investigation, is an analysis of the ability of the container to withstand preclosure handling accidents. Section 8.3.4.5.6, model validation investigation, is a summarization of all the efforts to develop documentation that demonstrates computer models used in the other three analyses are sufficiently trustworthy to use in calculations to support license application.

8.3.4.5.1 Purpose and objectives

The purpose of the waste package modeling program is to describe waste packages and appropriate corresponding sections of the repository by mathematical and computational models and to use these models to analyze the physicochemical phenomena that take place in and around the waste package. The analyses of the phenomena will produce predictions of waste package behavior that will enable waste package designs to be developed and licensed.

8.3.4.5.2 Rationale

Accuracy and realism of computer codes and models are required to assure that the codes and models reliably predict the phenomena they represent. The accuracy requirements for the various analyses in the waste package modeling program depend partly on the intended use of the results, and partly on the choices of experimental accuracy needs among many independent parameters. An example of the first kind of dependency is explained in detail in Section 8.3.4.5.3.2. The accuracy requirements that will be imposed on each code and model will be determined in terms of both the intended use of the code and model and the accuracy of the data that go into the model.

8.3.4.5.2.1 Regulatory rationale and issue resolution strategies

To show that regulations and issue resolution strategies are met, the BWIP must display analysis results dealing with all aspects of waste package behavior relevant to radionuclide containment and controlled release.

The four investigations that compose the waste package modeling program are necessary to meet Federal regulations that require defensible predictions of waste package reliability and performance that must accompany license application. Regulation 10 CFR 60 (NRC, 1987a) requires waste packages to prove substantially complete containment of radionuclides for a period between 300 and 1,000 yr. This regulation also restricts the fractional release rates of radionuclides from the engineered barriers after containment failure. Regulation 40 CFR 191 (EPA, 1986) restricts the cumulative releases of radionuclides to the accessible environment for a period of 10,000 yr. Regulation 10 CFR 20 (NRC, 1987b) sets limits for radiation exposure to the public and to repository operations personnel.

The issue resolution strategies related to the waste package modeling program are primarily Issues 1.1, 1.2, 1.4, and 1.5. In particular, Issues 1.4 and 1.5 each contain alternative paths that comply with the overall goals of the issues. For example, the preferred path through Issue 1.4 is to rely on the container and packing to meet the requirement for substantially complete containment of radionuclides. However, the alternate strategy is to rely on the container, the packing, and the waste form. In the former case, no model of the radionuclide dissolution process is necessary--all radionuclides are assumed to be dissolved completely upon contact with water.

In the latter case, however, it is necessary to account for the time-dependent radionuclide dissolution process by geochemical analysis. The most comprehensive case is assumed for the waste package modeling program, and all the relevant physicochemical phenomena affecting the waste package are taken into account. These analyses must cover anticipated and unanticipated event scenarios. The formulation of unanticipated event scenarios is discussed in Section 8.3.5.

8.3.4.5.2.2 Rationale for analysis methods

The techniques used in the analysis of each phenomenon affecting waste package performance in the containment or controlled release of radionuclides are discussed in this section. A system analysis approach to assessing waste package reliability is also summarized. The organization of these analytical techniques into particular investigations is discussed in Sections 8.3.4.5.3 through 8.3.4.5.6. The computer codes are discussed in Section 8.3.5.

These analyses are also discussed in Section 8.2 in the context of analytical tools development and are represented in the analytical tools development tables.

8.3.4.5.2.2.1 Thermal analysis.

The temperatures in and near the waste packages are important for four distinct reasons. First, all waste package components and the host rock are subject to temperature limits. If these limits are exceeded, waste package or host rock performance is degraded unacceptably. Second, the container corrosion rate depends on temperature, especially as it pertains to the corrosive environment of the container. Third, radionuclide solubility and sorption are temperature dependent. Fourth, some physical properties are temperature dependent.

The time-dependent temperature profiles for the waste package are obtained by computer solution of the thermal conduction equation. (Use of the complete energy equation for two-phase flow is not ruled out for the most sophisticated license application design analyses.) The solution is also obtained for a sufficiently large region of the repository to permit proper boundary conditions to be established. Numerous codes are available for thermal conduction computations. The DOE currently plans to use codes of greater sophistication for analyses requiring greater accuracy and simpler codes for analyses in which the accuracy of the results is not so crucial. Specific thermal conduction codes are discussed in Section 8.3.5. The heat source description is obtained by computer analysis of the history of typical spent fuel to be enclosed in the waste package.

The maximum allowable component temperatures will be obtained from archival literature (for the metal components), DOE tests (for the packing), or by analysis (for the host rock). The host rock thermal stress analysis will be performed as described in Section 8.3.4.5.4.3.1.

8.3.4.5.2.2.2 Resaturation analysis.

During the emplacement period of the repository, the air pressure in the repository will be essentially atmospheric, and the saturation temperature of the groundwater that contacts the waste package will be about 100 °C. The temperatures throughout the waste packages for spent fuel waste forms will be above 100 °C, so groundwater approaching these waste packages during this period will be in the form of steam. When the repository is closed, the pressure will begin to rise to about 9.4 MPa (1,360 lbf/in²), which is above the saturation pressure at the waste package temperatures, and the steam will be replaced by liquid water. Since the corrosion rate is considerably greater under aqueous conditions, it is important to know when the resaturation occurs.

At present, the resaturation scenario is not well understood. The resaturation process will be modeled with an upgraded version of the GEOTHER code (Faust, 1983) discussed in Section 8.3.5, which the DOE is presently developing to model two- and three-dimensional problems and to give predictions in the temperature regimes expected near the waste packages.

Heat source data as used in the thermal analysis (Section 8.3.4.5.2.4.3) are also used by the GEOTHER code as a heat flux boundary condition at the packing inner surface. The code solves the coupled energy transport and groundwater flow equations in the packing and the host rock and gives time-dependent temperature, pressure, and flow rate at selected points in the solution region. The temperature solution in the container and waste form are not obtained by the GEOTHER code; this solution must be computed in the thermal analysis (see Section 8.3.4.5.4.3.1). The principal goal of the resaturation analysis is to obtain a saturation scenario for use in analysis of container lifetime.

8.3.4.5.2.2.3 Container lifetime analysis.

Container lifetime analysis is vital to support the contention that waste packages will comply with regulatory requirements on radionuclide containment and controlled release. In the reference issue resolution strategy for Issue 1.4, the container is required to serve as an independent barrier that can satisfy the criteria for substantially complete containment of radionuclides. Therefore, containers must be shown with high confidence to be capable of isolating radionuclides for a period up to 1,000 yr, and corrosion is the principal mechanism by which they can fail to achieve this goal.

Up to now, container corrosion analyses have relied on empirical correlations to represent uniform corrosion only. The DOE is currently developing a corrosion model, supported to the extent possible by theoretical arguments, that is expected to provide bounding predictions of corrosion rates for all corrosion processes that could be relevant to the waste package environment. This model is based on transport limitations on oxidants in the reactions that produce corrosion, supplemented by kinetics considerations as appropriate. For a particular choice of container material, the reactions

that would be involved in any possible corrosion mode are identified, and it is assumed that any corrosion reaction involving transport of an oxidant would proceed as fast as the transport of the involved oxidant would permit. For non-transport-limited reactions such as container dissolution, the kinetics equations are solved with conservative assumptions. This model will be used for container lifetime analysis in conjunction with empirical models for the most complete description of corrosion permitted by the available knowledge of the relevant corrosion mechanisms.

This approach has been tested in a preliminary fashion (Walton and Sagar, 1987) for a carbon steel container and the chemical reactions involved in the uniform corrosion of this material. However, the approach is equally applicable to other container materials and for localized corrosion modes.

The protective effects of corrosion-product layers will be taken into account to the degree feasible both in empirical and theoretically based corrosion modeling. Also, the effects of local breaks in the protective layer will be considered, which would result, for example, by settling of the container through the packing.

The criterion for container failure in the container lifetime analysis will be taken from the structural strength analysis, which will include buckling and fracture mechanics analyses. The results of the container lifetime analysis will be used to establish a corrosion allowance.

The container lifetimes will be distributed in time because of variations in corrosion rate among containers. These variations will result from several factors, some of which are more difficult to predict quantitatively than others. The following factors are presently recognized:

- Variation in container temperature resulting from different heat outputs of waste in different containers and from different locations in the repository.
- Variations in groundwater composition from one container location to another.
- Variations in thicknesses of containers as manufactured.
- Variations in material composition of containers.
- Variations in condition of containers as emplaced, including manufacturing defects, flaws acquired during handling, and residual stresses present.

Some of these factors may, singly or in combination, determine which type of corrosion mechanisms are active.

In the performance sensitivity investigation, the sensitivity of container lifetime will be found to the variations in temperature, groundwater composition (including the effects of different packing saturation times), and

container properties and condition. This investigation will be performed deterministically in order to determine which factors influence container lifetime most significantly.

In the performance and reliability investigation, factors that have significant influences will be accounted for by Monte Carlo sampling of the data that describe the variations in these factors. The temperature variations can be predicted with high confidence, because the variations in waste form heat loading can be estimated accurately, and the thermal response of the repository can be calculated with high confidence. Variations in dimensions, composition, and condition of containers as manufactured can be estimated with high confidence from knowledge of such variations in similar manufactured objects. Variations in groundwater composition will be known with at least moderate confidence from site characterization measurements, experimental hydrothermal measurements, and geochemical modeling. The Monte Carlo sampling of input data will lead to distributed corrosion rate and container lifetime predictions.

The distributed container lifetime predictions will result from two kinds of variations in the input data: (1) actual differences in the values of the various influential factors among containers and (2) data variations that result from uncertainty in the values of parameters pertaining to all containers. The first type of parameter variation will lead to an actual distribution of container failures in time, whereas the second type of parameter variation will only lead to an uncertainty in the value of the mean container lifetime. An error analysis will be performed in the performance and reliability investigation to identify the uncertainties in the analysis so that these two kinds of variations in the container lifetime predictions can be distinguished.

8.3.4.5.2.2.4 Radionuclide release and transport analysis.

The release and transport of radionuclides after container failure must be analyzed for comparison with regulatory limits. The large number of radionuclides present in the waste forms will first be screened for importance. The screening will be based on radiotoxicity, the EPA release criteria, and the NRC release rate criterion. The equation of mass transport will then be solved by computer for each important radionuclide, accounting in the reliability analyses for stochasticity in the values of such properties as radionuclide solubility and rock porosity. The data base for the probability distribution functions of distributed parameters will be obtained in the testing and site characterization programs (Sections 8.3.4.2 and 8.3.4.3). Radionuclide releases by gaseous transport mechanisms will also be considered.

The output from this analysis will consist of release predictions or probability distribution functions for releases of all significant radionuclides present in the waste forms. These results will indicate whether the waste package system succeeds in meeting the fractional release rate and cumulative release regulations that apply (1) to the packing as an independent barrier for substantially complete containment and (2) to the waste package for gradual release in the time interval following the containment period.

8.3.4.5.2.2.5 Radiation shielding and radiolysis analysis.

The purposes of the radiation shielding and radiolysis analysis are as follows:

- Provide assurance that all waste packages are essentially unaffected by corrosion resulting from the products of groundwater radiolysis.
- Ensure radiological safety of repository operations.

First, the gamma-ray dose rates in groundwater in the packing and host rock will be calculated by computer. The radiation source strength of the waste forms will be either an upper limiting value or a range of source strengths, as appropriate for a given investigation. These dose rates will be used to estimate the radiolytic exacerbation of container corrosion. Corrosion by radiolysis products will be constrained by design to be negligible compared with the aqueous corrosion in the absence of such products. (The exact numerical value of the limit on radiolytic corrosion has not been decided. In the SCP conceptual design analysis (see Section 7.4.6.2.2), a limit of 10% of the aqueous corrosion was chosen.)

The effects of groundwater radiolysis by alpha particles on waste form dissolution will also be considered. Alpha particles have a very short range in water, about 10^{-5} m (3.3×10^{-5} ft), and they consequently have the potential to strongly affect groundwater chemistry very close to the waste form surface once the container has been breached and allowed groundwater to enter. The localized nature of alpha-particle energy deposition justifies the representation of the waste form surface as a plane, and a straightforward closed-form solution is anticipated for the dose rate adjacent to a unit area of the surface.

Ideally, radiolytic exacerbation of container corrosion would be determined in three steps. In the first step, the radiation doses would be used to provide source terms in the chemical kinetics equations for the radiolysis reactions. In the second step, these kinetics equations would be solved for the concentrations of radiolytic products. In the third step, these concentrations would be used in the mechanistic corrosion model to permit direct computation of corrosion by radiolytic products. Plans to apply computer codes to solve the kinetics equations are discussed below. Plans to develop a mechanistic corrosion model are described in Section 8.3.4.5.2.2.3. However, until such methods are available, an alternate method of inferring the radiolytic corrosion from radiation dose rates is required. This will be accomplished by obtaining an empirical correlation of dose rate with corrosion rate; experiments to measure radiolytic corrosion rates are discussed in Section 8.3.4.3.4.3.1.

The codes MAKSIMA-CHEMIST (Carver et al., 1979) and RADIOL (Simonson, 1985) are being considered for use in the solution of the chemical kinetics equations with radiolytic source terms. Input for these codes will consist of specification of the reactions, the rate constants governing the reactions at the anticipated temperatures, and the initial concentrations of the reactants.

Gamma-ray dose rates will also be calculated for living tissue in air near waste packages to assess radiological safety for workers in the anticipated repository operating conditions. Packing may or may not be included in the waste package model for these calculations, depending on the waste package emplacement scenario, and supplementary shielding may be added to the model if necessary to ensure adequate operational safety.

Methods for calculating the gamma-ray dose rates are currently being evaluated and compared. Previous waste package gamma-ray dose rate estimates have been made by a point-kernel ray-tracing method by which only the contribution of the primary (unscattered) gamma rays is computed accurately. Secondary (scattered) gamma rays are accounted for by an approximate augmentation technique (a buildup factor). Methods that are more accurate, but more costly, involve solution of the gamma-ray transport equation (i.e., the Boltzmann equation or the integral transport equation) by either finite-difference or statistical techniques.

8.3.4.5.2.2.6 Criticality analysis.

It will be necessary to prevent the waste packages from attaining nuclear criticality at any time in the future of the repository. If criticality were to occur, the resulting nuclear chain reaction would begin to produce new fission product nuclei (i.e., new high-level waste radionuclides). Because the unburned fissile isotopes in the waste forms have half-lives from 24,000 yr (^{239}Pu) to 7×10^8 yr (^{235}U), it is essential to ensure that all waste packages are inherently incapable of becoming critical.

All waste package configurations proposed for the repository must be checked for potential criticality by application of criticality codes. It must be determined that no plausible arrangement of the waste form or invasion by groundwater would be capable of creating a critical condition in any waste package.

The proximity of a system to nuclear criticality is expressed in terms of the neutron multiplication constant k_{eff} , which equals unity for a critical system. For preclosure criticality safety, 10 CFR 60 (NRC, 1987a) requires that k_{eff} be kept below 0.95.

There are many computer codes that can, when properly applied, compute k_{eff} to an accuracy within 5% for a correctly described system. Examples are KENO (Petrie and Landers, 1981), MORSE (West et al., 1984), and TWODANT (Alcouffe et al., 1984). However, uncertainties about the configuration of the system after degradation will lead to uncertainties greater than 5% in the value of k_{eff} . Peer-reviewed engineering judgment of these uncertainties, will be applied to postclosure conditions to arrive at a margin of at least 5% from criticality after allowance for uncertainties.

8.3.4.5.2.2.7 Structural strength analysis.

The container in the waste package must be shown to be capable of satisfying an appropriate structural standard, which is being developed (Section 8.3.4.4.3.3.3). This standard will specify the external loads for which the container will be designed and the analytical techniques that may be used to show that the container can withstand the external loads. These loads will include the repository hydrostatic pressure and may include in situ rock stresses or localized forces from the collapse of some portion of the host rock around the waste package. Calculations of structural integrity will include fracture mechanics analyses (including residual stress effects) to determine the ability of flawed containers to resist rupture by gradual flaw growth or environmentally assisted cracking. Because the container may be ductile, these fracture mechanics analyses will use nonlinear models. Also, the susceptibility of the container to buckling caused by creep and development of time-dependent mechanisms leading to loss of ductility will be investigated. The loads on the container will include additional pressure resulting from the swelling of the packing. Furthermore, the container must be shown to be capable of withstanding impact loads from certain handling accidents during preemplacement operations.

Packing subsidence will be analyzed by a viscoelastic model to find the distance by which the container will settle into the packing while in the borehole. This displacement would shorten the path by which radionuclides could travel from the waste form to the host rock. The computer codes ABAQUS (Hibbitt et al., 1985) and ADINA (ADINA, 1981) have the capability to represent viscoelastic phenomena. To apply these codes to a specific problem requires data on the variation of viscosity with respect to stress. These data will be obtained in the packing materials testing investigation described in Section 8.3.4.3.5.

8.3.4.5.2.2.8 Geochemical analysis.

Geochemical analysis is required to determine the anticipated groundwater composition and mineralogy as affected by the interactions with the packing, host rock, and container. These interactions will evolve over time so that the groundwater will change in composition over time, as well as being a function of space. The groundwater composition is expected to control the character of the container corrosion and radionuclide dissolution processes. The BWIP geochemical analysis uses the Lawrence Livermore National Laboratory code package EQ3/6 (Wolery, 1979), which is believed to be the best available code system for the purpose. The code EQ3 takes input that characterizes the groundwater (e.g., the concentrations of all chemical elements in solution) and solves for the equilibrium concentrations of all chemical species present (i.e., compounds and radicals). Also, EQ3 computes the degree of saturation of the species in the solution, with respect to mineral phases, at the groundwater temperature. The code EQ6 analyzes the interaction of the groundwater, composed as determined by EQ3, with some source of chemical species such as the host rock or the waste form. The output of EQ6 includes prediction of the masses of rock and waste form dissolution and mineral precipitation.

The geochemical analysis activity will be coupled with the resaturation analysis activity to address the following factors:

- Concentrations of solutes as functions of time at the boiling interface.
- Precipitation of solutes as functions of time at the boiling interface.
- Degree of boiling point elevation at the boiling interface because of effects of solutes.
- Effects of solutes on the motion of the boiling interface and on its approach to the packing and container wall.

These considerations must be dealt with to properly characterize the waste package environment as discussed in Section 8.3.4.2.3, so that subsequent steps in waste package analysis can be performed with proper input.

For accurate results, EQ3 requires an accurate data base. Accuracy needs for data will be determined through sensitivity analyses (explained in detail in Section 8.3.4.5.2.2). Because of the complexity of waste package behavior, it is often possible to compensate for uncertainties in some parameters by requiring greater certainty in others.

8.3.4.5.2.2.9 System analysis.

Unlike the phenomenological techniques described in Sections 8.3.4.5.2.2.1 through 8.3.4.5.2.2.8, system analysis techniques focus on the interactions among the components of a system. One such approach is the failure mode and effects analysis. This is a system analysis technique in which the different failure modes of the waste package components are identified, and the consequences of these failure modes on other system components and on the system function as a whole are assessed. A failure mode and effects analysis is called for by the Generic Requirements Document on Waste Package Reliability Analysis (NRC, 1985).

In the context of a failure mode and effects analysis, the term "failure mode" has a precise meaning. The term refers to an event or action that leads to an unsuccessful state of the system. For example, in the case of a safety valve that is designed to open at some specified pressure to protect a hydraulic system, the principal failure mode is failure to open at the specified pressure. Underlying causes for this failure mode, such as corrosion or a mechanical jam, are failure mechanisms rather than failure modes.

In the waste package failure mode and effects analysis, an attempt will be made to identify all possible waste package component failure modes and to estimate their probability. These estimates of probability will account for the foreseeable failure mechanisms and their probabilities of occurrence. The consequences of these failure modes on other components and on overall system function will also be analyzed.

8.3.4.5.3 Performance sensitivity investigation

Specific features of the performance sensitivity investigation are discussed in this section. The mathematical basis for the investigation is provided in Section 8.3.4.5.3.2, and the details of the individual analysis activities that pertain uniquely to this investigation are described in Section 8.3.4.5.3.3.

8.3.4.5.3.1 Purpose and objectives

This investigation will determine the sensitivity of waste package performance to variations in design parameters and material properties. Waste package performance is determined by the ability of the waste package to satisfy regulatory requirements on radionuclide containment and controlled release. Quantitatively, the performance is measured by container lifetime, radionuclide release rates, and cumulative releases. Variations in these performance measures will be computed as responses to variations in all relevant material properties and design parameters over their anticipated possible ranges. For simplicity in the interpretation of computed results, only deterministic codes will be used in the performance sensitivity investigation.

The purposes of studying these performance variations are to guide design and testing activities and put the waste package performance allocation on a more rigorous basis. The values of design and performance goals and confidence levels that have been set for design parameters and material properties at the beginning of the waste package program were, in most cases, based on sparse data and an incomplete understanding of the ways in which these quantities affect the overall radionuclide containment and release performance. This sensitivity investigation will quantify the relationships between waste package performance and the design parameter/property level goals and confidence levels. Consequently, these goals and confidence levels can be refined so that their simultaneous satisfaction for all design parameters and material properties will ensure the overall waste package containment and release performance and reliability goals are met. Also, the selection of goals and confidence levels for material properties must be made with consideration for the economics of the testing programs. Confidence levels for properties that are expensive to measure may not need to be as high as those for properties that can be more economically measured, depending on the strength of their effects on waste package performance.

8.3.4.5.3.2 Rationale

The mathematical basis of the performance sensitivity investigation is discussed below. This discussion explains how the sensitivity coefficients are used to relate indications of confidence in system element performance measures to indications of confidence in parameter values. These sensitivity coefficients are the partial derivatives of the performance measures with respect to the parameter values, evaluated at the mean values of the performance measures.

In principle, a performance measure of the waste package subsystem, R_S , is functionally related to the independent physical and design parameters, P_j , as follows:

$$R_S = h(P_1, \dots, P_m). \quad (8.3.4.5-1)$$

In general, h cannot be found in closed form because it is the solution of a complicated differential equation or system of differential equations that must be solved numerically. If a particular value is chosen for R_S , there is no unique solution for the combination of P_j values that give R_S ; in the performance allocation process, the investigator must use judgment to select a combination of parameter values that does satisfy Eq. 1 and also makes sense from practical considerations, including subjective factors (e.g., peer acceptance).

There are several ways by which the indications of confidence of the parameter values may be related to the indication of confidence of the subsystem performance measure. One method that is convenient to apply for waste package analysis is described here. First, we note that the confidence level of the value of a given parameter is related to its mean and variance. For example, a $(1-\alpha)$ 100% confidence interval for the mean value μ of a parameter with variance σ^2 is

$$X - Z_{\alpha/2} (\sigma/n^{1/2}) < \mu < X + Z_{\alpha/2} (\sigma/n^{1/2}) \quad (8.3.4.5-2)$$

where X is the mean of a sample of size n and $Z_{\alpha/2}$ is the value of the abscissa of the standard normal distribution function with an area of $\alpha/2$ on the right (Walpole and Meyers, 1972). If an adequate sample size has been obtained, the sample variance can be used as an approximation of the population variance.

Next, the mean and variance of the performance measure R_S are related to the mean values and variances of the parameters P_j :

$$\underline{R}_S = h(\underline{P}_1, \dots, \underline{P}_m) \quad (8.3.4.5-3)$$

where the underbars denote mean values, and

$$\text{var}(R_S) = \sum_{i=1}^m (\partial h / \partial P_i)^2 \text{var}(P_i) \quad (8.3.4.5-4)$$

where $\text{var}(Y)$ denotes the variance of any quantity Y (Hahn and Shapiro, 1967). This expression is only exact if h is a linear function of the P_i but is often used as an approximation for moderately nonlinear functional relationships. It is acknowledged that the numerical results obtained in the performance sensitivity investigation will be most reliable in regions of parameter space near the reference configuration.

The parameter-level indications of confidence must be chosen by the investigator in such a way that they not only lead to the desired indication of confidence for R_S when taken together but also individually reflect reasonable and appropriate expectations of the test programs in which the data will be obtained. There is no unique set of parameter-level indications of confidence that give a particular indication of confidence for R_S .

Then the variance of R_S can be related to the indication of confidence of R_S by another application of Eq. 2.

The substance of the performance sensitivity investigation is to find the sensitivity coefficients, $(\partial h / \partial P_i)$. This will be accomplished by individually varying the parameters P_i about their mean values in calculations of the performance of a reference waste package design using appropriate computational models. The reference configuration will be the SCP conceptual design for consolidated spent fuel. The performance measures for the waste package subsystem will be the release of radionuclides during the containment period (up to 1,000 yr after repository closure) for comparison with the requirements for the resolution of Issue 1.4 and the release rates of radionuclides from 1,000 to 10,000 yr after closure for comparison with the requirements for the resolution of Issue 1.5. These performance measures will be calculated by the application of models of thermal transport, radiation shielding and radio-lysis, container corrosion, and radionuclide release and transport, as discussed below.

The performance sensitivity investigation first will be conducted before or in parallel with the 30% phase of the advanced conceptual design program and will be updated before or in parallel with the 30% phase of the license application design. Because the SCP conceptual design will probably be used as a starting point for the advanced conceptual design, the SCP conceptual design waste packages will be used as reference configurations from which the variations in design parameters and material properties will be made in the advanced conceptual design phase of the investigation. The final advanced conceptual design will be used in the license application design phase of the investigation.

The design parameters and material properties that will be varied in this investigation are listed in Table 8.3.4.5-1 with anticipated ranges of variation when known. The results of the investigation will contribute to the resolution of Issue 1.4 by providing guidelines for the refinement of data on which the temperature history calculations will be based in the performance and reliability investigation. The results of the performance sensitivity investigation will also contribute to the resolution of Issue 1.5 by providing guidelines for the refinement of data on which calculations of the temporal

Table 8.3.4.5-1. Property variations for performance sensitivity investigation

Parameter or property	Expected range
Waste form specific heat	225 - 1,000 J/kg·K
Waste form thermal conductivity	0.35 - 3.0 W/m·K
Waste form density	2,500 - 7,000 kg/m ³
Waste form burnup	15,000 - 40,000 MWd/MTM
Waste form age at emplacement	5 - 20 yr
Radionuclide solubility (depends on species)	10 ⁻⁶ - 10 ² mg/L
Radionuclide sorption coefficient (depends on species)	0 - 250 mL/g
Packing specific heat	500 - 750 J/kg·K
Packing thermal conductivity	0.35 - 0.70 W/m·K
Packing density	1,500 - 2,000 kg/m ³
Packing thickness	0.1 - 1.0 m
Packing porosity	0.2 - 0.4
Packing diffusivity	10 ⁻⁵ - 10 ⁻⁴ cm ² /s
Packing hydraulic conductivity	TBD
Packing saturation time	0 - 100 yr
Packing formation factor (for tortuosity)	1 - 100
Packing moisture content (fraction of complete saturation)	0% - 100%
Host rock specific heat	775 - 1,000 J/kg·K
Host rock thermal conductivity	1.30 - 1.75 W/m·K
Host rock porosity	0 - 0.01
Host rock diffusivity	10 ⁻⁶ - 10 ⁻⁴ cm ² /s
Host rock hydraulic conductivity	10 ⁻¹⁰ - 10 ⁻¹² cm/s
Host rock formation factor (for tortuosity)	1 - 100
Container thickness	5.0 - 15.0 cm

PST87-2005-8.3.4.3

distribution of container failure and radionuclide releases are based. These data include radionuclide solubilities, radionuclide sorption behavior, diffusivities, and porosities, which are specifically called out in the information needs for Issue 1.5.

The flow of information between the performance sensitivity investigation and the test programs is a two-way process. Current values of all the parameters identified in the issue resolution strategies for Issues 1.4 and 1.5 (Section 8.2) will be used in the performance sensitivity investigation analysis activities. The results of these analyses will be used to identify the necessary improvements in the data base for these parameters, which must be obtained in the test programs.

The investigation includes computations in a number of separate analytical areas. The results of analyses in one area are often used as input to analyses in other areas. The different analyses that compose the performance sensitivity investigation and the relationships among these analyses are discussed in Section 8.3.4.5.3.3.

Analytical efforts performed by the design subcontractor to support trade and feasibility studies (Section 8.3.4.4) for the waste package also fall under the scope of the performance sensitivity investigation. These analytical efforts will involve the same technical areas, with the exception of the radionuclide release and transport analysis, as those considered by the BWIP but from different points of view and with different analytical tools.

8.3.4.5.3.3 Description of activities

The specific technical analysis areas included in the performance sensitivity investigation are discussed in this section.

8.3.4.5.3.3.1 Thermal transport sensitivity analysis activity.

Thermal transport analysis is basic to the analyses of container lifetime and radionuclide release because of the dependency of these performance measures on temperature. The temperature contours in the waste package and host rock will depend on waste form decay power output; packing thickness and density; and waste form, packing, and host rock thermal conductivity and specific heat. These quantities will be varied in the ranges shown in Table 8.3.4.5-1.

The objective of the analysis is to obtain temperatures throughout the waste package and the modeled portion of the repository at selected times in the repository history for all combinations of input parameters required to evaluate the sensitivity coefficients. This effort will require numerous runs of a thermal transport code. Therefore, a relatively simple, fast-running code such as TSAP (Kao, 1982) will be chosen for this work. The initial part of the analysis will consist of developing the input data file to model the waste package and the associated part of the repository in the manner required for the code that is chosen.

The assortment of time-dependent temperature contours that results from the thermal analysis will be used as input in the container lifetime and radiolysis analyses and eventually in radionuclide release analyses. Also, combinations of input parameters that cause waste package component or host rock temperatures to exceed their allowable limits will be used to determine a phase-space boundary on permissible waste package decay-heat loading. That is, for any combination of material properties and packing thickness, the limit on permissible decay-power output can be established.

8.3.4.5.3.3.2 Resaturation sensitivity analysis activity.

The GEOTHER code (Faust, 1983), which will be used for resaturation analysis, is currently being modified to model the three-dimensional configuration of the waste package and surrounding repository and to give accurate results in rock at the temperatures expected near the waste packages. This modification is largely complete, but some refinements remain to be completed. Also, the need to include dissolution and exsolution of noncondensable gases is being considered. As part of this development effort, an input data file will be written to define the geometrical and physical model of the repository. The methodology will be applied to the license application design portion of the performance sensitivity investigation.

The objective of the activity is to analyze the repository resaturation process for a comprehensive selection of input parameters. In particular, it is important to know the packing saturation time (i.e., the amount of time that passes before liquid water contacts the container surface). Variations in the packing saturation time will be computed for variations in packing and host rock porosity, thermal conductivity, specific heat, density, and waste form decay-heat output. The varying saturation times will be fed into the corrosion computations and will serve as one of the sources of the spread in container lifetimes.

8.3.4.5.3.3.3 Container lifetime sensitivity analysis activity.

A corrosion model based on theoretical arguments is under development to supplement the strictly empirical model used previously in container lifetime analyses (Section 8.3.4.5.2.2.3). The theoretically based model will be used to bound the corrosion rates predicted by the empirical model. This model will be ready for use in time for the license application design phase of the performance sensitivity investigation. The empirical model will be used alone for the advanced conceptual design phase.

When the theoretically based model is available, container life will be computed both for oxidizing and reducing environments for the purpose of comparing lifetimes, but the empirical model is based only on a reducing environment.

Containers will be assumed to fail when their walls are reduced by corrosion to a thickness determined by structural analysis techniques.

The purposes of the container lifetime calculations in the performance sensitivity investigation are as follows:

- Determine the sensitivity of container lifetime to variations in material properties and design parameters.
- Obtain input for the radionuclide release and transport analysis.

The material properties and design parameters variations have effects on container lifetime arising through their influence on container temperature. (Corrosion rates are functions of temperature in three ways. First, temperature, together with pressure, determines whether the environment is aqueous or air/steam. Second, in either environment, corrosion is at least slightly temperature dependent. Third, the corrosion caused by radiolytic products is temperature dependent.) This influence will be separately determined by the thermal transport analysis (Section 8.3.4.5.3.3.1). The various temperature solutions will be used as input to the corrosion calculations. The objective of this analysis is to find container lifetimes that result from different temperature history inputs.

Container lifetime variations also arise from variations in container thickness but in such an obvious way that sensitivity analysis of this dependency is not necessary.

One of the most significant factors in determining the container corrosion rate is the timing of packing saturation. A method for analyzing packing saturation is being developed (Section 8.3.4.5.2.2.2). However, the method will not be ready in time for the advanced conceptual design phase of this sensitivity investigation. Therefore, in the advanced conceptual design phase, the packing saturation time will also be varied parametrically in the container corrosion analysis, as indicated in Table 8.3.4.5-1. For the license application design phase of this investigation, the packing saturation time will be found in the resaturation analysis discussed in Section 8.3.4.5.3.3.2.

The container lifetimes are important results in themselves because of their relationship to the containment requirement in 10 CFR 60 (NRC, 1987a). However, they also provide the input to the radionuclide release and transport analysis by marking the onset of radionuclide release.

8.3.4.5.3.3.4 Radionuclide release and transport sensitivity analysis activity.

This analysis will determine the sensitivity of waste package controlled-release performance to variations in radionuclide solubility, and to variations in hydraulic conductivity, diffusivity, tortuosity, porosity, and radionuclide sorption in both packing and host rock. These parameters will be varied in the ranges shown in Table 8.3.4.5-1. Specifically, the objective of the analysis is a comprehensive set of solutions for radionuclide releases covering the ranges of input parameters chosen for consideration.

The computational models used in this analysis are already substantially developed and have been applied in previous analytical work by the BWIP. These models are embodied in the codes CHAINT (Kline et al., 1985) and CHAINT-MC (Baca et al., 1984), which are described in some detail in Section 8.3.5. The geometrical and physical models will be encoded as input files to these computer codes. If the code CHAINT-MC is used in this analysis, it will be run in a deterministic mode because the sensitivity coefficients are evaluated only at the mean values of the performance measures.

8.3.4.5.3.3.5 Radiation shielding and radiolysis sensitivity analysis activity.

The specific objectives of this analysis are to compute gamma-ray dose rates for all the combinations of input parameters chosen for consideration and to estimate the radiolytic contribution to container corrosion resulting from the postemplacement gamma-ray doses in groundwater.

The gamma-ray dose rate in groundwater will be found at selected locations in the packing and nearby host rock as the following quantities are varied: container thickness, packing thickness, waste form age and burnup, and packing moisture content. Postemplacement radiolytic effects on container corrosion will probably be assessed through an empirical correlation of radiolytic corrosion with gamma-ray dose.

The early stages of this analysis will involve code selection and development of geometrical and physical models for incorporation into input files. Codes being considered for the shielding computations include QADMOD-G (Price and Blattner, 1979), TWODANT (Alcouffe et al., 1984), and MORSE (West et al., 1984) (Section 8.3.5). It is likely that a simple code like QADMOD-G will prove sufficiently accurate for the purposes of this sensitivity investigation.

The effect of resaturation time on radiolytic corrosion is especially important, because gamma-ray fluxes are greatest in the period immediately after emplacement. If there is no liquid water adjacent to the container at the time of greatest gamma-ray flux, relatively little radiolysis of water can occur, but radiolytic decomposition of nitrogen in the air/steam environment can lead to the production of nitric acid. The variation of radiolytic corrosion with resaturation time is one of the relationships that will be determined in the performance sensitivity investigation.

8.3.4.5.3.3.6 Geochemical sensitivity analysis activity.

In the advanced conceptual design phase of the performance sensitivity investigation, prior geochemical analysis results will be used to justify the use of empirical corrosion correlations obtained in a chemically reducing environment. When a mechanistic corrosion model is available, and when the radionuclide transport code is modified to accept a time-dependent

concentration boundary condition at the waste form surface, detailed geo-chemical analyses using the EQ3/6 code package (Wolery, 1979) can be used to provide input to the corrosion and transport analyses.

8.3.4.5.3.3.7 Structural strength sensitivity analysis activity.

Trade studies and feasibility studies performed by the design subcontractor (Section 8.3.4.4.3.3.1) will require analytical support in the form of structural strength analyses. The precise nature of these analyses cannot be clarified until the trade studies and feasibility studies have begun.

The objectives of the structural strength analyses will be to answer specific design-oriented structural questions that arise in the trade and feasibility studies. Appropriate mathematical, computational, geometrical, and physical models will be developed or selected for the specific problems that arise in the course of the trade and feasibility studies.

8.3.4.5.3.4 Application of results

The results of the performance sensitivity investigation will be used to guide design and testing activities and to refine the performance allocation. Table 8.3.4.5-2 specifically displays the relationships between this investigation and other investigations.

8.3.4.5.3.5 Schedule and Milestones

As stated previously, the performance sensitivity investigation will be coordinated with the 30% phases of the advanced conceptual design and license application design. The second portion of the investigation will be performed during the final phases of the advanced conceptual design. Separate milestone reports will be issued at the completion of each of these phases of the investigation. The schedule for the waste package performance sensitivity investigation is displayed in Figure 8.3.4.5-1.

8.3.4.5.4 Performance and reliability investigation

This section gives details of the performance and reliability investigation. The differences between this investigation and the performance sensitivity investigation are explained in detail because the two investigations superficially resemble each other. Then, the unique aspects of the individual analysis activities are discussed.

8.3.4.5.4.1 Purpose and objectives

This investigation encompasses all of the analyses performed by the design subcontractor and the BWIP to support the development and documentation of the waste packages for all waste forms considered in the design effort.

Table 8.3.4.5-2. Relationships between performance sensitivity investigation and other investigations

Investigation affected	Study affected (section)	Parameters affected
Postemplacement environment characterization	Basalt/groundwater interactions (8.3.4.2.3.3.1)	Temperature
	Geochemical environment (8.3.4.2.3.3.2)	Temperature
Natural analogs and metallic artifacts	Natural analogs (8.3.4.2.4.3.1)	Temperature
Waste forms	Waste acceptance specifications (8.3.4.3.3.3.4)	Waste heat loading limit per waste package
Packing materials	Physical properties and processes (8.3.4.3.5.3.2)	Specific heat, thermal conductivity, density, hydraulic conductivity, porosity, tortuosity
Waste package radionuclide behavior	Radionuclide sorption and solubility (8.3.4.3.6.3.1)	Radionuclide sorption and solubility
Design activities	Trade and engineering studies (8.3.4.4.3.3.1)	Waste package dimensions and materials
	Container design and construction standard development (8.3.4.4.3.3.3)	Container materials and structural properties
Qualification testing	Packing saturation test (8.3.4.4.6.3.2)	Hydraulic conductivity, porosity, tortuosity

PST87-2005-8.3.4-4

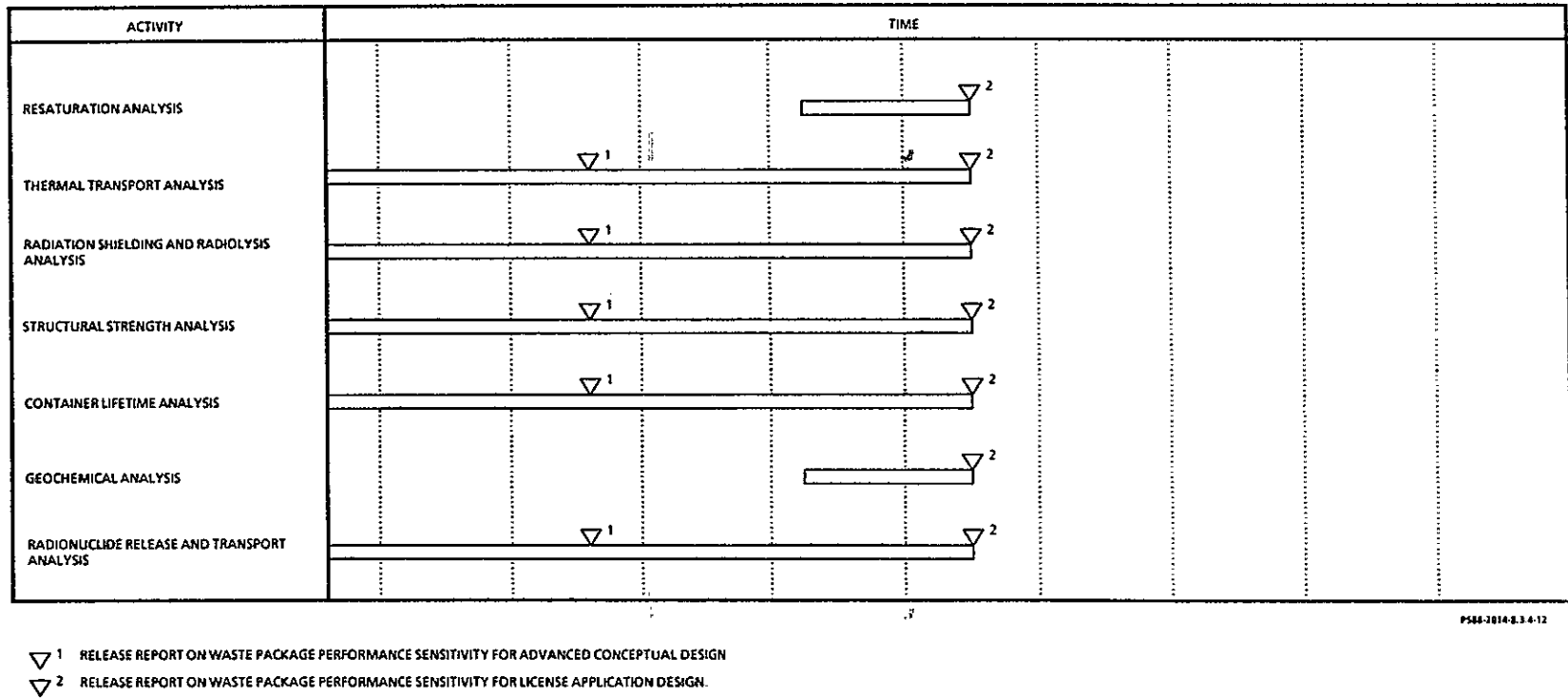


Figure 8.3.4.5-1. Waste package performance sensitivity investigation.

The purposes of the investigation are (1) to provide a basis for choice among alternative approaches to solving design problems and (2) to support the contention that the final waste package configurations can satisfy regulatory requirements.

The objective of the investigation is to synthesize the results of the individual analyses into integrated evaluations of the ability of the waste packages to satisfy performance and reliability requirements. In some cases, the same analysis will be used to evaluate more than one aspect of waste package performance and reliability.

8.3.4.5.4.2 Rationale

The performance and reliability investigation is intended to support the design and assess the performance of specific configurations proposed in the various stages of the advanced conceptual design and license application design activities.

The architect-engineer will perform design analyses concurrently with the development of design configurations. After specific configurations are selected, the architect-engineer will perform design verification analyses, to recheck the conformance of selected configurations with design requirements. Subsequently, the integrating contractor will conduct independent analyses to assess the ability of proposed configurations to meet the containment and controlled release requirements of the issue resolution strategies.

All of these phases of the performance and reliability investigation will include some or all of the technical areas involved in the performance sensitivity investigation, as well as criticality and systems analysis activities not covered in the performance sensitivity investigation. However, the application of the individual technical areas is considerably different because of the focus of the analyses on design development and statistically based reliability analysis.

Although reliability is an aspect of performance, the term is used here specifically to refer to measures of performance that are probabilistic (i.e., measures in which the probability is found that the waste package component or system can perform its function for a specified time under specified conditions). Some portions of this investigation concern waste package reliability. The remainder of the investigation concerns the measures of waste package performance that can be modeled deterministically.

The reliability analysis begins with the thermal transport and packing saturation analyses that provide input data for the analyses of corrosion and radionuclide release and transport. Because of the uncertainty in thermal properties of the waste form, packing, and host rock, and because of the variation in waste form decay heat output, the thermal transport analysis will be probabilistic, and the results will consist of a statistically distributed range of temperature solutions for each waste form included in the proposed advanced conceptual design and license application design. Packing saturation

time will also be variable. These distributed results for temperature and saturation time will be used in the corrosion calculations to obtain distribution functions for container lifetimes. The temperature solutions, container lifetime solutions, and stochastic variation in radionuclide solubility and sorption data will be used to produce distribution functions for radionuclide cumulative releases and fractional release rates. The principal differences between this reliability analysis and the performance sensitivity investigation are the following:

- This analysis is performed for specific waste package design configurations under consideration for the advanced conceptual design and license application design.
- Variations in all parameters are taken into account simultaneously in this analysis.
- The material properties data may be updated from those used in the corresponding phases of the performance sensitivity investigation.
- Some analytical areas having no analogues in the performance sensitivity investigation are considered in this investigation.

The results of the corrosion and radionuclide release and transport analyses will be compared with the requirements on radionuclide containment and controlled release in 10 CFR 60 (NRC, 1987a) and 40 CFR 191 (EPA, 1986).

The reliability analysis will also include a system analysis: the failure mode and effects analysis.

The deterministic portion of the investigation will include analyses of structural strength, criticality, and radiation shielding and radiolysis. Upper bounding cases of the thermal transport analysis will be used as input to the structural strength and radiolysis calculations. The structural strength analysis will provide a criterion for container failure in the container lifetime analysis. These deterministic analyses are also coupled to the reliability analysis.

This investigation will contribute to the resolution of Issue 1.1 by predicting container lifetime, release rate, and temperature solutions and to the resolution of Issues 1.2 and 1.4 by predicting container corrosion, waste package and repository temperature histories, and container structural loading from packing expansion and corrosion product buildup. The results of the investigation will be used directly in the resolution of Issues 1.5 and 2.2. By contributing to the closure of these technical issues, the investigation will indirectly support the closure of Issues 1.3 and 1.10.

All of the parameters identified in the issue resolution strategies for Issues 1.4, 1.5, and 2.2 (see Section 8.2) will be used in these analyses.

8.3.4.5.4.3 Description of activities

Analyses in specific technical areas are discussed below.

8.3.4.5.4.3.1 Thermal transport analysis activity.

The objective of this activity is to compute, at selected times in the life of the repository, temperature contours in the waste package and host rock for each candidate waste package design with several combinations of waste form decay-power output and packing and host rock thermal conductivity, specific heat, and density. The specific combinations of input parameters will be determined based on test results and performance sensitivity investigation results. The results of the thermal transport calculations will be applied to the analyses of corrosion, radionuclide release and transport, structural strength, and radiolysis as stated in Section 8.3.4.5.4.2. Temperature solutions are needed in the structural strength analysis to determine temperature-dependent material properties and whether the waste package and host rock temperature limits are exceeded.

In this investigation, accuracy of results is more important than in the performance sensitivity investigation, in which the variations in performance resulting from variations in properties and parameters are primarily sought. Also, not nearly as many computer runs will be needed in this investigation. Therefore, it is appropriate to use a more accurate but slower and more costly computer code. At the present time, it is expected that the SINDA code (Smith, 1971) will be used in these calculations. Part of the analytical activity will involve setting up input files for SINDA (Smith, 1971) or an alternative code to establish the geometrical and physical models of the waste package and repository.

8.3.4.5.4.3.2 Resaturation analysis activity.

The GEOTHER code (Faust, 1983), which will be used for the resaturation analysis, will be modified (1) to model the three-dimensional geometrical configuration of the waste package and surrounding repository, and (2) to give accurate results in rock at the temperatures expected near the waste packages (Section 8.3.4.5.3.3.2). Beginning with the 85% advanced conceptual design phase, the methodology will be applied to the performance and reliability investigation.

This analysis will comprise computations to represent the resaturation process occurring in the repository host rock and in the packing of the proposed waste package design configurations. Because the thermodynamic state of the water in and near the waste package depends on the temperature distribution, resaturation calculations will be performed with a range of waste form decay-heat outputs. Variability of packing and host rock porosity, thermal conductivity, specific heat, and density will also be taken into account. The objective of the analysis will be a table of packing saturation times for the different ranges of property values and heat loadings. These results will be incorporated into the input of the container corrosion calculation and will, therefore, contribute to the statistical variation in the container lifetimes.

8.3.4.5.4.3.3 Container lifetime analysis activity.

The theoretically based corrosion model should be available by January 1988, which is in time for the update of the performance and reliability investigation for the 85% phase of the advanced conceptual design. The empirical model previously employed, which is contained in the PCM.STAT code (Section 8.3.5), and which is based on a reducing environment during most of the postclosure period, will be used by itself until the mechanistic model is available, and subsequently in concert with the mechanistic model.

The statistically varied results of the thermal conduction and resaturation calculations will be used as input in the container corrosion calculations. These calculations will result in statistically distributed container lifetime predictions. The objective of the analysis is to compute for each proposed waste package design a cumulative probability distribution function for container failure; the complement of this function is the container reliability as a function of time. The reliability function will be used to judge the degree to which the waste packages comply with the radionuclide containment requirements of 10 CFR 60 (NRC, 1987a). The container lifetime distribution functions will be used as input to the radionuclide release and transport analysis.

When the theoretically based model is available, container life will also be computed assuming a scenario of an oxidizing environment.

8.3.4.5.4.3.4 Radionuclide release and transport analysis activity.

The computational models used in this analysis for dissolved radionuclides are already substantially developed, as discussed in Section 8.3.4.5.3.3.4; they are embodied in the CHAINT (Kline et al., 1985), CHAINT-MC (Baca et al., 1984), and REPREL (Eslinger and Sagar, 1985) codes (see Section 8.3.5). The geometrical and physical models will be encoded as input files to these computer codes. The statistical features of CHAINT-MC will permit the ranges of parameter values to be accounted for in the input.

The results of the container lifetime analysis will provide statistically varied input to the radionuclide release and transport calculations. By the time these calculations have begun, the temperature dependencies of radionuclide solubility and sorption will be included in the radionuclide release and transport model, so that the variation in the thermal conduction results will also be incorporated into the input for these calculations.

Models for the analysis of gaseous transport of radionuclides in a basalt repository have not been developed. However, the possibility of gaseous releases will be considered, and, if necessary, models for the calculation of gaseous release rates will be adapted from the literature or developed as part of the waste package modeling program.

The objective of the radionuclide release and transport calculations is to produce probability distribution functions for fractional release rates and cumulative releases for all significant radionuclides from all the advanced conceptual design and license application design waste package configurations. These results will be used to judge the ability of the waste package designs to comply with the radionuclide release requirements of 10 CFR 60 (NRC, 1987a) and 40 CFR 191 (EPA, 1986) and with the siting criteria of 10 CFR 960 (DOE, 1987a).

8.3.4.5.4.3.5 Radiation shielding and radiolysis analysis activity.

The code selection process completed in support of the radiation shielding analysis in the performance sensitivity investigation will also provide the basis for selecting radiation shielding codes for the performance and reliability investigation. Because accuracy of results is more important in this investigation than in the sensitivity investigation, a more accurate code may be needed even if it costs substantially more to run. It is expected that a deterministic radiation transport code such as TWODANT (Alcouffe et al., 1984) will be chosen for axisymmetric waste packages, and that a Monte Carlo code such as MORSE (West et al., 1984) may be chosen for waste packages, such as those for intact spent fuel assemblies, that are not axisymmetric. A substantial effort is required to prepare input data files for any of these codes to ensure that the representation of physical properties and geometry and the selection of numerical quadrature options lead to an accurate and converged solution.

Because it is required that none of the waste packages in the repository suffer significantly greater corrosion from the action of groundwater radiolysis products than they would in the absence of such products, this study will be performed deterministically, in that unique values of material properties will be chosen for each design configuration. If a Monte Carlo code is used, the radiation transport equation will be solved statistically; the output will contain a statistical uncertainty arising from the limited number of gamma-ray histories computed. This uncertainty can always be reduced by tracking more gamma-ray histories. The input will consist of a single set of property values and dimensions for each waste package design configuration rather than distributions over ranges of values. Therefore, this planned use of a Monte Carlo radiation shielding code is not probabilistic in the same way as the use of a Monte Carlo radionuclide transport code, which samples uncertain input values in a large number of runs of the code and obtains statistically distributed output to which the only refinement obtainable from additional runs is a refinement of the output distribution function. Design-dependent parameters such as packing and container thickness will be established by the architect-engineer for each waste package configuration, but for uncertain parameters such as host rock density and variable parameters such as waste form decay-heat output, conservative upper bounds will be taken. This analysis will be used as a screening device to determine whether any proposed waste package configurations are unable to meet the criterion of negligible radiolytic corrosion. Those that fail to meet the criterion will be rejected.

The specific objectives of the analysis will include groundwater gamma-ray dose rates in the packing and nearby host rock for all the combinations of input parameters chosen for consideration. These dose rates will be used to estimate the effects of radiolysis on container corrosion and to assess radiological safety during repository operations.

Radiolytic corrosion will be assessed by empirical correlations of corrosion exacerbation with dose rates, and after a mechanistic corrosion model is available, by the solution of the kinetics equations for the production of corrosive radiolysis products in a gamma-radiation field. For the operational safety assessment, gamma-ray doses in living tissue will be found near the waste packages before emplacement. The presence of packing in any of the preemplacement waste package models will depend on the operating and emplacement scenarios. Additional shielding may be included if it is shown to be necessary.

Alpha-particle radiolysis and its effect on radionuclide dissolution in the controlled release period will be assessed by a simple closed-form solution for dose rates and the application of kinetics equation for the dissolution chemistry.

8.3.4.5.4.3.6 Criticality analysis activity.

The waste package design configurations proposed by the design subcontractor will be checked for potential nuclear criticality. It is known that a single disintegrated fresh pressurized water reactor fuel assembly in a steel waste disposal container filled with water can be supercritical (Gore et al., 1980). Eventual invasion of the waste package container by groundwater is a normal operating condition. Therefore, it is evident that some minimum fissile concentration must be specified for fuel assemblies accepted for the repository.

The objective of this activity is to determine what measures are required to ensure that waste packages do not attain nuclear criticality either before or after emplacement. This information will be obtained in the following three steps:

1. The neutron multiplication constant k_{eff} will be obtained for proposed waste package designs with fresh fuel and no water in the container. The absence of water is expected to cause these waste packages to be substantially subcritical, even if a filler material is included in the voids between fuel rods. However, it is necessary to confirm that a filler material does not have enough neutron-moderating capability to create a criticality hazard.
2. The maximum allowable fissile fuel content will be determined for proposed waste package designs after intrusion by groundwater, but before any rearrangement of the waste form that might result from the deterioration process. (It may be necessary to assume that low-burnup, highly enriched fuel assemblies are dismantled and combined with high-burnup fuel to keep the fissile fuel in any one waste package below the allowable maximum.)

3. Reasonable scenarios will be developed for the deterioration of waste packages in ways that result in the rearrangement of the waste form. For example, the heavy fuel pellets may settle into the bottoms of the waste containers and become more closely packed together. The neutron multiplication factor k_{eff} will be found for these rearranged waste packages. It is not known a priori whether such rearrangements will increase or reduce k_{eff} . If the assumed rearrangement reduces the potential for criticality, the proposed waste package design will be considered acceptable from the standpoint of criticality safety; otherwise, a reduction in fissile fuel content will be imposed.

There are many computer codes that can be used to compute k_{eff} for waste packages. In many respects, selection of one of these codes is a matter of the user's preference and the ease of adapting particular codes to the computing equipment available. At the present time it is expected that a deterministic radiation transport code such as the TWODANT code (Alcouffe et al., 1984) will be used for axisymmetric waste packages, and possibly for all the criticality calculations. A Monte Carlo code such as the KENO code (Petrie and Landers, 1981) may be used for waste packages that are not axisymmetric. A substantial effort will be required to set up the input data files for any of these codes to ensure that the representation of geometry and physical properties and selection of quadrature options lead to accurate and converged solutions. This effort would be considerably greater for Monte Carlo codes.

8.3.4.5.4.3.7 Structural strength analysis activity.

Throughout the development of the waste package designs, stress and deformation analyses must be performed to ensure that the containers can withstand the structural loads that will be imposed on them. These stresses and deformations are the objectives of the calculations discussed in this section.

After repository resaturation, waste packages will be subjected to an external hydrostatic pressure of approximately 9.4 MPa (1,360 lbf/in²). It is yet to be determined whether an additional load from collapsed host rock should also be taken into account; this determination will be made through an analysis of the host rock (Section 8.3.2.2).

A design standard for waste package containers will be developed in time for the 60% phase of the license application design; a draft will be ready for application to the 85% phase of the advanced conceptual design. Until the draft standard is ready, containers will be designed to meet the Standards of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code for Class I Components (ASME, 1983), as was the case for the SCP conceptual design.

Specific structural in-service failure modes for which proposed waste containers will be analyzed include buckling of the cylindrical wall, head collapse, plastic hinge failure at the junction of the cylindrical wall and head, and nonductile failure (i.e., sudden extension of a flaw with little or no plastic deformation). Buckling induced by creep will be investigated, and the possibility of occurrence of mechanisms that could reduce ductility will be considered. The loads on the container will include the additional pressure resulting from packing swelling. Previous analyses performed for the SCP conceptual design are summarized in Section 7.4.6.2.3.

An additional structural analysis will be performed for waste packages, including packing, undergoing the emplacement operation. This analysis will consist of application of a finite-element stress code to waste packages as they are held by handling equipment and emplaced. (The packing may be pre-emplaced into the borehole before the container, or placed over the container before emplacement and inserted with it.) The deflections predicted by the computer calculations will determine the practicality of suggested emplacement techniques.

Packing subsidence will be analyzed to find the distance by which the container can be expected to settle into the packing during its long residence in the borehole. This displacement would shorten the path by which radionuclides would travel from the waste form to the host rock. A viscoelastic model will be employed for this analysis.

The calculations described above will require a number of separate model development and code selection efforts that will be initiated and updated as appropriate throughout the activity.

8.3.4.5.4.3.8 Geochemical analysis activity.

In the advanced conceptual design phase of the performance and reliability investigation, prior geochemical analysis results will be used to justify the adoption of empirical corrosion correlations obtained in a chemically reducing environment. If the effort to develop a mechanistic corrosion model is successful, and when the radionuclide transport codes are modified to accept a time-dependent concentration boundary condition at the waste form surface, detailed geochemical analyses using the EQ3/6 code package (Wolery, 1979) can be used to provide input to the corrosion and transport analyses.

8.3.4.5.4.3.9 System analysis activity.

A failure mode and effects analysis first will be performed in parallel with the 30% phase of the advanced conceptual design. The objectives of the analysis are as follows:

- Identify waste package component failure modes.
- Discover the interrelationships among waste package components that lead from component failures to degraded performance or failure of other waste package components, or failure of the waste package subsystem.

- Quantitatively estimate the probabilities of the various failure modes so identified.

The analysis will continually be updated throughout the advanced conceptual design and license application design efforts as newly gained information permits identification of previously unrecognized failure modes or relationships among system components, and as refinements in the phenomenological analyses (discussed in Sections 8.3.4.5.4.3.1 through 8.3.4.5.4.3.8) permit more accurate estimation of the failure probabilities that form the quantitative aspect of the failure mode and effects analysis.

In addition, attempts will be made to identify or develop new system analysis techniques to supplement the failure mode and effects analysis.

8.3.4.5.4.4 Application of results

The results of the performance and reliability investigation will be used to guide design activities. This section presents the relationships between this investigation and design investigations in Table 8.3.4.5-3.

Table 8.3.4.5-3. Interties between performance and reliability investigation and other investigations

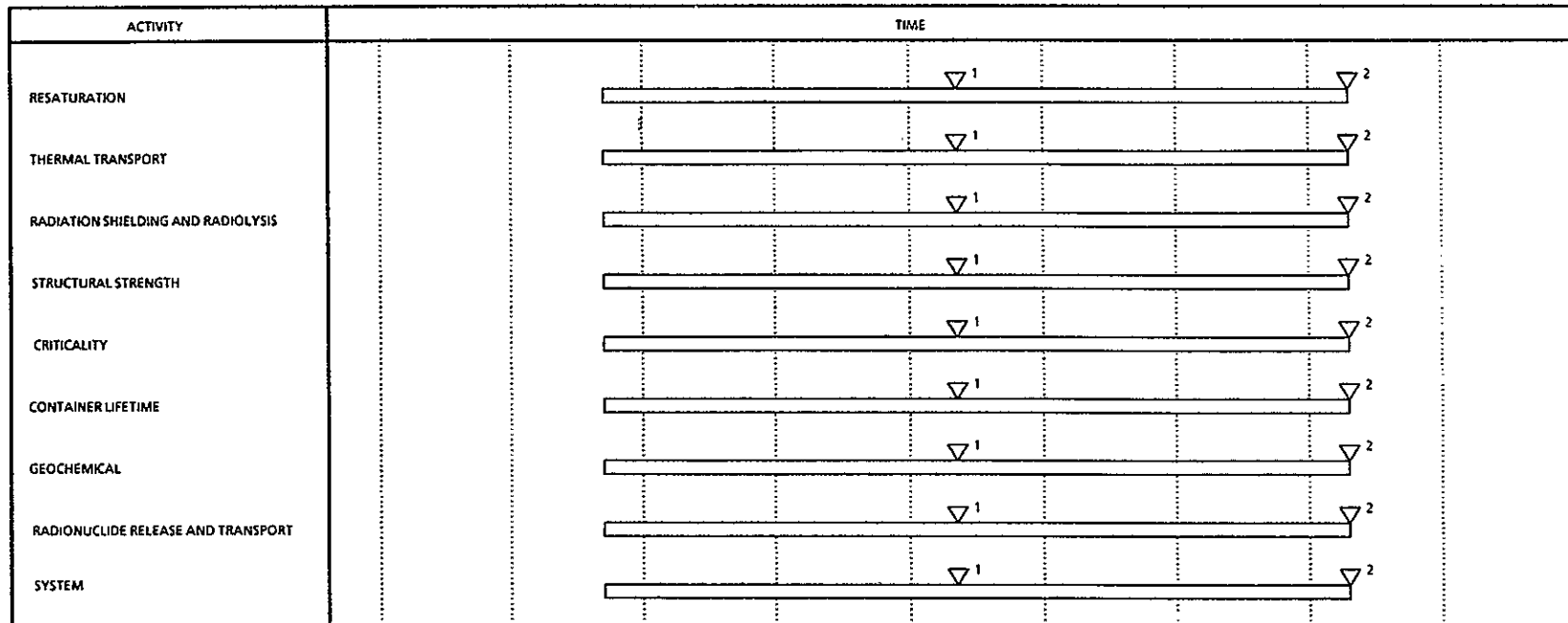
Investigation affected	Study affected (section)	Parameters affected
Design activities	Waste package configuration (8.3.4.4.2.3.2)	Waste package dimensions and materials
Packing development	Packing handling and emplacement (8.3.4.4.5.3.3)	Packing composition, dimensions, and emplacement technique

8.3.4.5.4.5 Schedule and Milestones

The performance and reliability investigation will be performed throughout the advanced conceptual design and license application design projects. The work will be reported in the design reports issued at completion of the 60%, 85%, and final phases of these design efforts. A schedule coordinating the analytical investigation with the designs is shown in Figure 8.3.4.5-2.

8.3.4.5.5 Impact stress and fracture investigation

This investigation provides container fracture information that is needed to assess radiation exposure from postulated accidents.



PS06-2014-0.7 4-13

▽¹ RELEASE REPORT ON WASTE PACKAGE PERFORMANCE AND RELIABILITY FOR ADVANCED CONCEPTUAL DESIGN.

▽² RELEASE REPORT ON WASTE PACKAGE PERFORMANCE AND RELIABILITY FOR LICENSE APPLICATION DESIGN.

Figure 8.3.4.5-2. Waste package performance and reliability investigation.

8.3.4.5.5.1 Purpose and objectives

The purpose of this investigation is to confirm the ability of waste containers to withstand the impact stresses imposed on them during certain specified handling accidents that might occur during repository operations. The plan for identification of specific accidents to be considered is discussed in Section 8.3.5.1. The objective of the investigation is to determine the loads, stresses, and deformations the containers would experience during the specified accidents and to compare them with failure criteria to determine whether failure would occur.

8.3.4.5.5.2 Rationale

The impact stress and fracture model to be applied in this investigation will be developed by a subcontractor in parallel with the 30% phase of the advanced conceptual design. The model will then be applied in conjunction with the remaining phases of the advanced conceptual design to verify the adequacy of the proposed design configurations. The model will be upgraded if necessary during the 30% phase of the license application design and will be applied to the proposed license application design configurations during the remainder of the license application design effort.

The investigation will aid in the resolution of Issues 2.1, 2.2, 2.3, and 2.4 concerning radiation exposure from normal operations and abnormal occurrences during operations and closure. The investigation will make this contribution by providing information on the extent of damage to containers from postulated accidents. This damage information will be used to assess radiation exposure to workers and the public.

8.3.4.5.5.3 Description of activity

The activity will consist of a structural strength analysis with the impact stress and fracture model discussed in Section 8.3.4.5.5.2. The objective of the analysis is to compute the impact stresses and deformations and compare them with container failure criteria for all specified accident scenarios.

Some existing computer codes are capable of solving impact stress and fracture problems; ABAQUS (Hibbitt et al., 1985) and ADINA (ADINA, 1981) are examples of such codes. Impact stress and fracture problems are difficult nonlinear problems that must be solved iteratively because neither the load nor the deceleration and deformation are known independently: they must be found together. The user of the code must provide a subroutine that describes the stress-strain response characteristics of the surface onto which the container will fall; the surface will be characterized as completely rigid in this analysis. Also, he must provide the description of the geometry and the material properties of the container, and its kinetic energy on impact. Furthermore, he provides an initial guess of the load history between the container and the impact surface. The code will compute the deceleration and deformation of the container under the assumed loading. Because the

deformation and deceleration of the container will not be compatible with the zero-displacement boundary condition of the impact surface, the code user must make another guess for the load history. The process must be repeated until the deformation and deceleration histories are consistent with the boundary condition. One of the main challenges of this type of approach is to find a way to converge from the initial guess to the correct solution.

8.3.4.5.5.4 Application of results

The results of the impact stress and fracture investigation will be used to guide design activities. Specifically, the results will support the container handling and safety testing study of the container development investigation, as presented in Table 8.3.4.5-4.

Table 8.3.4.5-4. Interties between impact stress and fracture investigation and other investigations

Investigation affected	Study affected (section)	Parameters affected
Container development	Container handling and safety testing (8.3.4.4.4.3.4)	Container materials and dimensions

8.3.4.5.5.5 Schedule and milestones

As in the performance and reliability investigation, the impact stress and fracture investigation will be performed throughout the advanced conceptual design and license application design projects. The work will be reported in the design reports issued at the completion of the 60%, 85%, and final phases of these design effort. A schedule coordinating the analytical investigation with the designs is shown in Figure 8.3.4.5-3.

8.3.4.5.6 Model validation investigation

The plans to document and test computer codes and models to be used in the waste package modeling program are discussed in this section.

8.3.4.5.6.1 Purpose and objectives

The purpose of this investigation is to confirm that computer models used in analytical studies are reliable to give accurate, realistic solutions for the problems to which they are applied. The term "computer model" is used to denote a computer code together with the data used to represent a particular physical system.

8.3.4.3-34

ACTIVITY	TIME
IMPACT STRESS/FRACTURE	
	<div>▽¹</div> <div>▽²</div>

PS&H 2014-0.3-A-14

▽¹ CONTRIBUTE SUMMARY OF IMPACT STRESS/FRACTURE ANALYSIS FOR THE ADVANCED CONCEPTUAL DESIGN REPORT.

▽² CONTRIBUTE SUMMARY OF IMPACT STRESS/FRACTURE ANALYSIS FOR THE LICENSE APPLICATION DESIGN REPORT.

Figure 8.3.4.5-3. Impact stress/fracture investigation.

A general discussion of the philosophy of model validation for application to geologic repositories is presented in Section 8.3.5.3.4. In that discussion, it is pointed out that the time scale of geologic repository functional requirements is so great that only a partial validation is possible. A complete classical validation would require direct experimental corroboration of models by full-scale, full-duration testing. The partial validation available for repository computer models will rely on peer review, limited experiments and field investigations, natural analogue studies, and theoretical scoping calculations.

This section presents specific elements of the application of the philosophy explained in Section 8.3.5.3.4 to waste package computer models.

8.3.4.5.6.2 Rationale

Model validation is the process of assuring that a computer model is a correct representation of the process or system for which it is intended, and that the predictions of the code adequately reflect the relevant phenomena in the real world.

The first step in model validation is the verification of the computer code contained in the model. Verification contains a number of elements, as explained, for example, by Powell (1982). When a computer code is developed in accordance with modern software development techniques, verification is an integral part of its development. This verification process includes preparation of requirements documents, technical descriptions, user's guides, and acceptance testing plans, and the performance of tests for software function. Testing includes checks that the algorithm on which the code is based is executed as intended, as well as comparisons of code results with the solutions of simple problems for which closed-form solutions are obtainable. When possible, verification includes benchmarking, which involves comparing the results of the code being developed with the results of previously existing codes that can solve some of the same problems.

For codes that did not include the formal verification process in their development, it will be necessary to create whatever documentation is missing and perform acceptance testing to confirm that the codes perform their intended functions properly. This process is currently being conducted for all codes to be used in the waste package modeling program.

Once the codes have been verified, it will be necessary to perform the remaining portions of the partial validation process on the computer models to be used in the waste package modeling program. As stated above, the computer models comprise the codes and the data describing the actual physical system. In most cases, however, experimental validation of the actual computer models to be used in waste package modeling, including the data describing the repository conditions, cannot be performed. Instead, experiments or field tests will be performed that approximate the repository conditions as nearly as practicable, and computer models of these experiments will be formulated.

Peer review will be employed to decide whether (1) the computer models used for comparison with such experiments and field tests are sufficiently similar to the repository computer models and (2) whether the results produced by the former models agree sufficiently well with the experiments and field tests, to warrant a judgment that the repository models are validated.

The processes described above are required by NRC (1983) for all computer models to be used in the waste package modeling program. This is true even for codes that have been validated on computer systems other than those on which they will be run for the BWIP analyses. The verification processes are needed for such codes because of the possibility that machine-dependent idiosyncrasies of the codes may lead to different results on different machines. This possibility is especially likely for the several Monte Carlo codes planned for use in the waste package modeling program (see Section 8.3.5), which rely on machine-dependent random number generators.

8.3.4.5.6.3 Description of activities

The verification portion of the model validation investigation is a straightforward (although not always easy) matter of writing documents and running the codes to solve problems for which closed-form solutions can be found in the literature. It is not considered necessary to present detailed plans here for the verification of individual codes.

Also, the general validation strategy and peer review process are explained in Section 8.3.5.3.4 and are not reproduced here. The specific experiments and field tests that will be used to support the partial validation of the waste package computer models will be discussed in this section.

Validation of thermal transport models will partly be accomplished by analyzing the heat transfer in a sequence of waste package physical model experiments to be managed by the DOE. These experiments will involve a half-scale waste package mockup with heat sources representative of maximum allowable waste form thermal output. The experiments will yield thermal conduction measurements, as well as other results discussed below in connection with other studies. These measurements will enable correct thermal conductivity and specific heat values to be deduced for use in the thermal models.

The GEOTHER code (Faust, 1983) used for the resaturation analyses will be validated by analyzing the packing saturation experiments that will be performed on the half-scale physical model mentioned above. This validation process will enable correct values to be used in the model for packing porosity, hydraulic conductivity, diffusivity, and formation factor.

The mechanistic corrosion model currently under development will be encoded for computer solution and the resulting code will be benchmarked, verified, and validated in accordance with the regulations of the NRC (1983). The half-scale physical model experiments discussed above will include corrosion measurements to be used in validating the corrosion model.

Validation of the codes CHAINT (Kline et al., 1985) and CHAINT-MC (Baca et al., 1984) which are planned for use in the radionuclide release and transport analyses, can be accomplished by comparison of code predictions with fracture flowthrough and sorption tests to be conducted by the Materials Characterization Group (Section 8.3.4.2) and exploratory shaft cluster injection tests being planned by the Site Department (Section 8.3.1).

Validation of the codes and models used in the radiation transport and criticality calculations will be accomplished by comparing code predictions with experimental results available in the open literature.

All codes and models used in the structural analyses required to substantiate the final license application design will be benchmarked, verified, and validated as required by the NRC (1983). Validation will be achieved in the most convenient means available. In some cases, experimental results published in the open literature will be relied on; in other cases, such as the waste package emplacement test (Section 8.3.4.4), experimental results obtained by the DOE will be used.

8.3.4.5.6.4 Application of results

The results of this investigation will be used to justify the predictions made in the later stages of the license application design phase of the performance and reliability investigation and the impact stress and fracture investigation. The interties among these investigations are elaborated in Table 8.3.4.5-5.

8.3.4.5.6.5 Schedule and Milestones

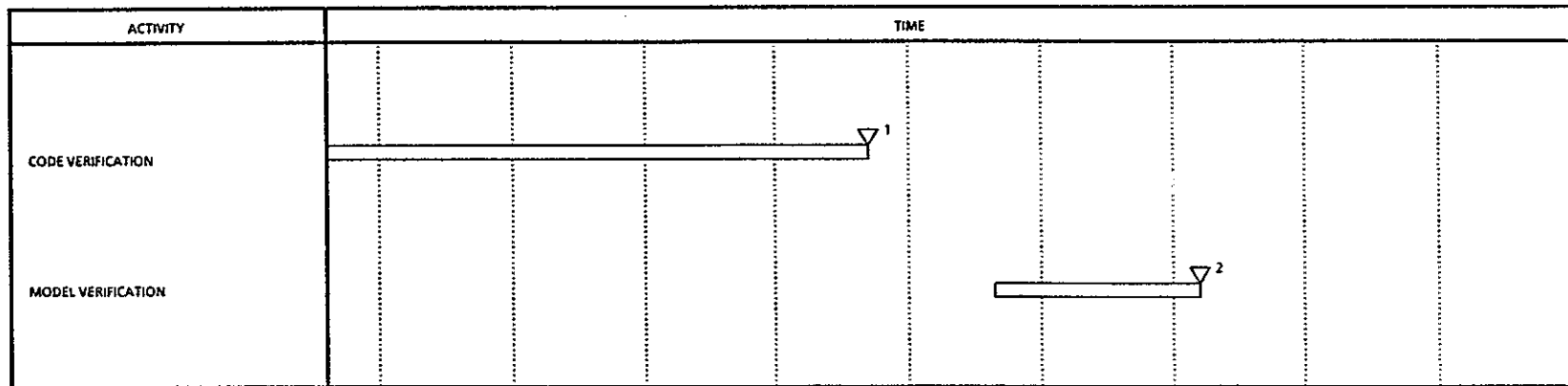
The model validation investigations will be performed throughout the advanced conceptual design and license application design projects. The work will be reported separately as completed for each code to be used in the final license application design. These reports will be issued not later than the end of the 60% phase of the license application design effort. If significant changes are made in the models after the 60% phase of the license application design, the validation studies will be updated accordingly. A schedule coordinating the analytical investigation with the designs is shown in Figure 8.3.4.5-4.

Table 8.3.4.5-5. Relationships between model validation investigation and other investigations

Investigation affected	Study affected (section)	Parameters affected
Performance and reliability	Thermal transport (8.3.4.5.4.3.1)	Thermal properties of materials and dimensions of components
	Resaturation (8.3.4.5.4.3.2)	Thermal and hydraulic properties of host rock and packing
	Container lifetime (8.3.4.5.4.3.3)	Rate coefficients in corrosion model
	Radionuclide release and transport (8.3.4.5.4.3.4)	Radionuclide solubility and sorption
	Radiation shielding (8.3.4.5.4.3.5)	Material compositions and geometry
	Criticality (8.3.4.5.4.3.6)	Material compositions and geometry
	Structural strength (8.3.4.5.4.3.7)	Structural properties and geometry
Impact stress and fracture	Container fracture (8.3.4.5.5.3)	Container materials and geometry

PST87-2005-8 3.4.7

8.3.4.5-39



PSM-2014-8.3.4-15

- ▽¹ COMPLETE FINAL INTERNAL DEVELOPMENT REVIEWS.
- ▽² RELEASE REPORT ON MODEL VALIDATION FOR LICENSE APPLICATION DESIGN.

Figure 8.3.4.5-4. Model validation investigation.

This page intentionally left blank.

9 2 1 2 5 5 5 0 8 3 8

8.3.4.6 References

- ADINA, 1981. ADINA - A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis, Report AE81-1, ADINA Engineering, Inc., Watertown, Massachusetts. [MF 0781]
- Alcouffe, R. E., F. W. Brinkley, D. R. Marr, and R. D. O'Dell, 1984. User's Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport, LA-10049-M, Rev. 1, Los Alamos National Laboratory, Los Alamos, New Mexico. [MF 0757]
- Anantatmula, 1987. Container Materials Testing: General Corrosion Study Plan, SD-BWI-SP-020 Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4941]
- ANSI/ASME, 1986. Quality Assurance Program Requirements for Nuclear Facilities, ANSI/ASME NQA-1, American National Standards Institute/American Society of Mechanical Engineers, United Engineering Center, New York, New York. [MF 0680]
- Apted, M. J., A. M. Liebetrau, D. W. Engel, D. H. Alexander, 1986. Analysis of Spent Fuel Performance in a Geologic Repository, PNL-SA-13928, Pacific Northwest Laboratory, Richland, Washington.
- Aronson, J. L. and M. Lee, 1986. "K/Ar Systematics of Bentonite and Shale in a Contact Metamorphic Zone, Cerrillos, New Mexico," Clays and Clay Minerals, Vol. 34, pp. 473-483.
- ASME, 1983. ASME Boiler and Pressure Vessel Code, Section III, Division 1, American Society of Mechanical Engineers, New York, New York, Sections NB-3133, NB-3200, NB-3211, and Appendices A and G.
- ASME Criteria Document, 1969. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2", ASME, United Engineering Center, New York, New York. [MF 4942]
- Baca, R. G., R. C. Arnett, and D. W. Langford, 1984. "Modeling Fluid Flow in Fractured Porous-Rock Masses by Finite Element Technique," International Journal for Numerical Methods in Fluids, Vol. 4, pp. 337-348. [MF 4640]
- Bain, G. M., 1987. Container Corrosion Qualification Testing Study Plan, SD-BWI-SP-017 Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Chamberlain, C. P., and P. Karabinos, 1987. "Influence of Deformation on Pressure-Temperature Paths of Metamorphism," Geology, Vol. 15, pp. 42-44. [MF 2709]
- Croff, A. G., 1980. A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code, ORNL 5621, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

- Coture, 1985. "Rapid Increases in Permeability and Porosity of Bentonite-Sand Mixtures Due to Alteration by Water Vapor," Mat. Res. Soc. Symp. Proc., Vol. 44, pp. 515-522.
- DOE, 1986. Environmental Assessment, Reference Repository Location, Hanford Site, Washington, DOE/RW-0070, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C. [MF 3175]
- DOE, 1987a. General Guidelines for the Recommendations of Sites for Nuclear Waste Repositories, Title 10, Code of Federal Regulations, Part 960, U.S. Department of Energy, Washington, D.C. [MF 4849]
- DOE, 1987b. Office of Geologic Repositories Issues Hierarchy for a Mined Geologic Disposal System (OGR/B-10), DOE/RW-0101, Rev. 1, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, Washington, D.C. [MF 4747]
- Duncan, D. R., 1987a. Container Materials Testing: Environmentally Assisted Cracking Study Plan, SD-BWI-SP-023 Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4943]
- Duncan, D. R., 1987b. Container Materials Testing: Mechanical and Physical Properties Study Plan, SD-BWI-SP-024 Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4944]
- England, P. C., and A. B. Thompson, 1984. Pressure-Temperature-Time Paths of Regional Metamorphism I. Heat Transfer During the Evolution of Thickened Continental Crust, Journal of Petrology, Vol. 25, Part 4, pp. 894-928. [MF 3399]
- EPA, 1986*. Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Title 40, Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, Washington, D.C. [MF 4906]
- Eslinger, P. W., and B. Sagar, 1985. REPREL Computer Code: User's Guide, RHO-BW-CR-148P, Rockwell Hanford Operations, Richland, Washington. [MF 0764]
- Faust, C. R., 1983. GEOOTHER: A Two-Phase Fluid Flow and Heat Transfer Code, ONWI-434, INTERA Environmental Consultants, Inc., Houston, Texas. [MF 0768]
- Fish, R. L., 1987. Container Materials Testing: Pitting Corrosion Study Plan, SD-BWI-SP-021 Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4945]

*A decision on July 17, 1987, by the U.S. Court of Appeals for the First Circuit has required the EPA to reconsider its postclosure standards (Subpart B) in 40 CFR 191. Consequently, the standards in 40 CFR 191 may be subject to revision in the future.

- Gilbert/Commonwealth, 1987. Site Characterization Plan Conceptual Design Report for BWIP High Level Nuclear Waste Packages, SD-BWI-CDR-005, Rev. 0, Gilbert/Commonwealth, Inc., for Rockwell Hanford Operations, Richland, Washington. [MF 3727]
- Gore, B. F., G. W. McNair, and S. W. Heaberlin, 1980. Criticality Safety Considerations in the Geologic Disposal of Spent Nuclear Fuel Assemblies, PNL-3268, Pacific Northwest Laboratories, Richland, Washington. [MF 1376]
- Hahn, G. J. and S. S. Shapiro, 1967. Statistical Models in Engineering, p. 231, Wiley, New York, New York. [MF 4542]
- Hibbitt, Karlsson, and Sorensen, Inc., 1985. ABAQUS User's Manual, Version 4.5(a), Providence, Rhode Island. [MF 4500]
- IT Corp., 1987a. Waste Package Environment = Basalt/Groundwater Interactions Study Plan, SD-BWI-SP-042 Rev. 0, International Technology Corporation for Westinghouse Hanford Company, Richland, Washington.
- IT Corp., 1987b. Waste Package Environment = Geochemical Environment Analysis Study Plan, SD-BWI-SP-003 Rev. 0, Corporation for Westinghouse Hanford Company, Richland, Washington.
- Kao, T., 1982. Thermal System Analysis Program (TSAP), Version 1.0.1, publ. by T. Kao, available through Gilbert/Commonwealth, Inc. [MF 4461]
- Kline, N. W., R. L. England, and R. G. Baca, 1985. CHAINT Computer Code: User's Guide, RHO-BW-CR-144, Rockwell Hanford Operations, Richland, Washington. [MF 1921]
- Nadeau, P. H. and R. C. Reynolds, Jr., 1981. "Burial and Contact Metamorphism in the Mancos Shale," Clays and Clay Minerals, Vol. 29, pp. 249-259.
- NAS, 1983. A Study of the Isolation System for Geologic Disposal of Radioactive Wastes, National Academy of Sciences, National Academy Press, Washington, D.C. [MF 1497]
- Neal, W. L., S. A. Rawson, and J. R. Burnell, 1987. Waste/Barrier/Rock Interactions: Spent Fuel Release Testing Study Plan, SD-BWI-SP-040, Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4947]
- NRC, 1983. Final Technical Position on Documentation of Computer Codes for High-Level Waste Management, NUREG-0856, U.S. Nuclear Regulatory Commission, Washington, D.C.
- NRC, 1985. U.S. Nuclear Regulatory Commission Generic Technical Position on Waste Package Reliability Analysis for High-Level Nuclear Waste Repositories, Nuclear Regulatory Commission, Washington, D.C.

- NRC, 1987a. Disposal of Nuclear Radioactive Waste in Geologic Repositories, Title 10, Code of Federal Regulations, Part 60, U.S. Nuclear Regulatory Commission, Washington, D.C., Section 60.113. [MF 4903]
- NRC, 1987b. Standards for Protection Against Radiation, Title 10, Code of Federal Regulations, Part 20, U.S. Nuclear Regulatory Commission, Washington, D.C. [MF 4904]
- Petrie, L. M. and N. F. Landers, 1981. KENO IV/S - An Improved Monte Carlo Criticality Program, NUREG/CR-0200, Vol. 2, Section F5, pp. F5.1.1-F5.1.2, Computer Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [MF 4539]
- Powell, P. B., 1982. Planning for Software Validation, Verification, and Testing, NBS Special Publication 500-98, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C. [MF 4948]
- Price, J. H., and G. M. Blattner, 1979, "QADMOD-G Point Kernel Gamma-Ray Shielding Code," RSIC Computer Code Collection, CCC-396, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [MF 3623]
- Rawson, S. A. and W. L. Neal, 1987. Waste/Barrier/Rock Interactions: Borosilicate Glass Release Testing Study Plan, SD-BWI-SP-041 Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Rawson, S. A., 1987a. Waste Package Metallic Artifacts Study Plan, SD-BWI-SP-025 Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4949]
- Rawson, S. A., 1987b. Waste Package Natural Analogs Study Plan, SD-BWI-SP-002, Rev. 0, Westinghouse Hanford Company, Richland, Washington. [MF 4950]
- Simonson, S. and W. Kuhn, 1983. "Predicting Amounts of Radiolitically Produced Species in Brine Solutions," PNL-SA-11426, Pacific Northwest Laboratory, Richland, Washington.
- Smith, J. P., 1971. SINDA User's Manual, MSC-18597, Computer Software Management and Information Center, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas. [MF 0778]
- Staudigel, H., K. Gillis, and R. Duncan, 1986. "K/Ar and Rb/Sr Ages of Celadonites From the Troodos Ophiolite, Cyprus," Geology, Vol. 14, No. 1, pp. 72-75. [MF 2710]
- Thompson, A. B., and P. C. England, 1984. Pressure-Temperature-Time Paths of Regional Metamorphism II. Their Influence and Interpretation Using Mineral Assemblages in Metamorphic Rocks, Journal of Petrology, Vol. 25, pp. 929-954. [MF 4465]

- Trone, P. M., and M. L. Cummings, 1987. Paragenesis of Secondary Precipitated Phases in Grande Ronde Basalt, Northeastern Oregon, RHO-BW-SA-650 A, Rockwell Hanford Operations. [MF 4466]
- Walpole, R. E. and R. H. Myers, 1972. Probability and Statistics for Engineers and Scientists, p. 188, Macmillan, New York, New York. [MF 4541]
- Walton, J. C. and B. Sagar, 1987. Corrosion Model for Nuclear Waste Containers, Scientific Basis for Nuclear Waste Management X, Materials Research Society, J. K. Bates and W. B. Seefeldt (eds.); also RHO-BW-SA-576, Rockwell Hanford Operations, Richland, Washington. [MF 4491]
- West, J. T., T. J. Hoffman, and M. B. Emmett, 1984. MORSE-SGC/S for the SCALE System, NUREG/CR-0200, Vol. 2, Section F9, pp. F9.1.1-F9.1.2, Computing and Telecommunications Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [MF 4540]
- Westinghouse, 1982. Waste Package Conceptual Designs for a Nuclear Repository in Basalt, RHO-BW-CR-136 P/AESD-TME-3142, Westinghouse Electric Corporation, Advanced Energy Systems Division, for Rockwell Hanford Operations, Richland, Washington. (MF 1552)
- Westinghouse, 1985. Evaluation of Alternative Waste Package Concepts for Spent Fuel, WTSD-TME-025, Rev. A, Westinghouse Electric Corporation, Waste Technology Service Division, for Rockwell Hanford Operations, Richland, Washington. [MF 4952]
- WHC, 1987. Waste Package Scenario Document, Westinghouse Hanford Company, Richland, Washington. [MF 4953]
- Wolery, T. J., 1979. Calculation of Chemical Equilibrium Between Aqueous Solutions and Minerals: The EQ3/6 Software Package, UCRL-52658, Lawrence Livermore National Laboratory, Livermore, California. [MF 2575]
- Wolery, T.J., 1983. "EQ3NR, A Computer Program for Geochemical Aqueous Speciation-Solubility Calculations: User's Guide and Documentation," UCRL-53414, Lawrence Livermore National Laboratory, Livermore, California.
- Wood, M. I., and IT Corp., 1987. Radionuclide Solubility/Sorption and Speciation Behavior Study Plan, SD-BWI-SP-039, Rev. 0, International Technology Corporation for Westinghouse Hanford Company, Richland, Washington. (to be issued)
- Yung, S. C., C. F. McLane, R. P. Anantatmula, R. T. Toyooka, and W. K. Terry, 1987. Waste Package Preliminary Reliability Analysis Report, SD-BWI-TI-287 Rev. 0, Rockwell Hanford Operations, Richland, Washington.
- Zavoshy, S., P. Chambre, and T. Pigford, 1985. "Mass Transfer in a Geologic Environment," C. Jantzen and R. Ewing (eds.) Scientific Basis for Nuclear Waste Management, Vol. 8, North Holland, New York, New York. [MF 4543]

This page intentionally left blank.

9 2 1 2 5 5 5 0 8 9 4